DEVELOPMENT OF A PROCEDURE TO MEASURE UNSTEADY PROPELLER FORCES

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Lieutenant Commander, U.S. Navy

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Submitted to the Department of Naval Architecture and Marine Engineering on 14 May 1971 in partial fulfillment of the requirements for the degree of Master of Science in Naval Architecture and Marine Engineering.

The procedure developed involves measuring the unsteady propeller forces derived from operating in a circumferentially non-uniform inflow. This involves wake generation and survey, force measurement, and data analysis. The study was undertaken to expand the capability of the M.I.T. Variable Pressure Water Tunnel to measure the six components (a force and moment in three dimensions) of unsteady propeller force. This is accomplished by foil and semiconductor strain gages applied to the stiff driveshaft on which the propeller is mounted. These signals are amplified, signal averaged, and computer analyzed for harmonic content. Strain gage waterproofing and electrical wiring problems encountered resulted in a limiting of the objective to partial dynamometer operation. This necessitated a more detailed description of the apparatus than usual, so that future experimenters may use this information as design history to complete the six component capability.

Thesis Supervisor: Justin E. Kerwin

Title: Professor of Naval Architecture

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

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And finally my wife, Sally, my grammatical editor and typist, who not only coped with my indifferent handwriting, but also inspired me in darker moments.

I - INTRODUCTION

This study concerns the measurement of the fluctuating forces produced on a propeller operating in a circumferentially non-uniform velocity field. This is of obvious concern to the Naval Architect designing propellers to operate in the wake of ships.

The circumferential non-uniform inflow causes variations in the inflow velocity and (although not as significant) angle of attack which results in time-varying local loading of the propeller blades. These forces are transmitted to the ship hull via the shafting and bearings, often causing serious mechanical vibration and noise radiation. The forces that are produced in this manner are called Wake-bearing Forces, and always derive from the non-uniform flow.

Wake-bearing Forces are not the only propeller generated forces that affect a ship. The local pressure field surrounding the rotating propeller is seen at a fixed point on the hull as a time-varying pressure fluctuation. Unsteady forces transmitted to the hull in this manner are known as Pressure Forces. They are not a consequence of the uniformity, or the non-uniformity of the inflow velocity field.

There is a third form of hull-propeller force interaction mechanism known as the Interference-bearing Force. As the name implies, unsteady loading on the hull produces a reaction on the propeller. The resulting unsteady forces on the propeller are transmitted via shafting and bearings back to the hull producing vibration and acoustic radiation. Just as Pressure

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Forces, the Interference-bearing Forces occur regardless of the uniformity of the inflow velocity.

Objective

The objective of this thesis is to further the capability of the M.I.T. Variable Pressure Water Tunnel by developing a procedure to measure simultaneously all the force and moment components of the shaft transmitted unsteady forces, including recording and analysis in a timely fashion. The particular experiment undertaken to proof this procedure development was designed to obtain a fundamental set of accurate experimental measurements of the unsteady forces of an arbitrary propeller operating in a circumferentially non-uniform inflow.

Importance

During the past decade, shipbuilders have become more aware of their need to have some insight into the dynamic characteristics of the screw propulsion systems they were designing into the more powerful ships. Larger more powerful propulsors, and more high speed craft not only meant bigger problems in the sterntube bearing and thrust block due to the vibratory loading, but acoustic radiations from these same vibratory forces interfered with sound measurement, and militarily became more important as more precise sensors evolved and subsurface vehicles strove for more dense operating depths. Early experimenters [1] [2]* only measured unsteady Torque and Thrust to size thrust block and gearing. Wereldsma of the Netherlands Ship Model Basin became the first to measure all six

* Numbers in brackets designate References.

components [3], the last four components (horizontal and vertical forces and movements) being needed to accurately define the entire mechanical load of the sterntube and strut -if existing- bearing(s).

The possibility of using partially submerged screw propellers in surface effect ship thrusters [4] makes an additional case for the necessity to measure all the components (in this case the steady side and vertical force is definitely not zero) in both a steady and unsteady mode.

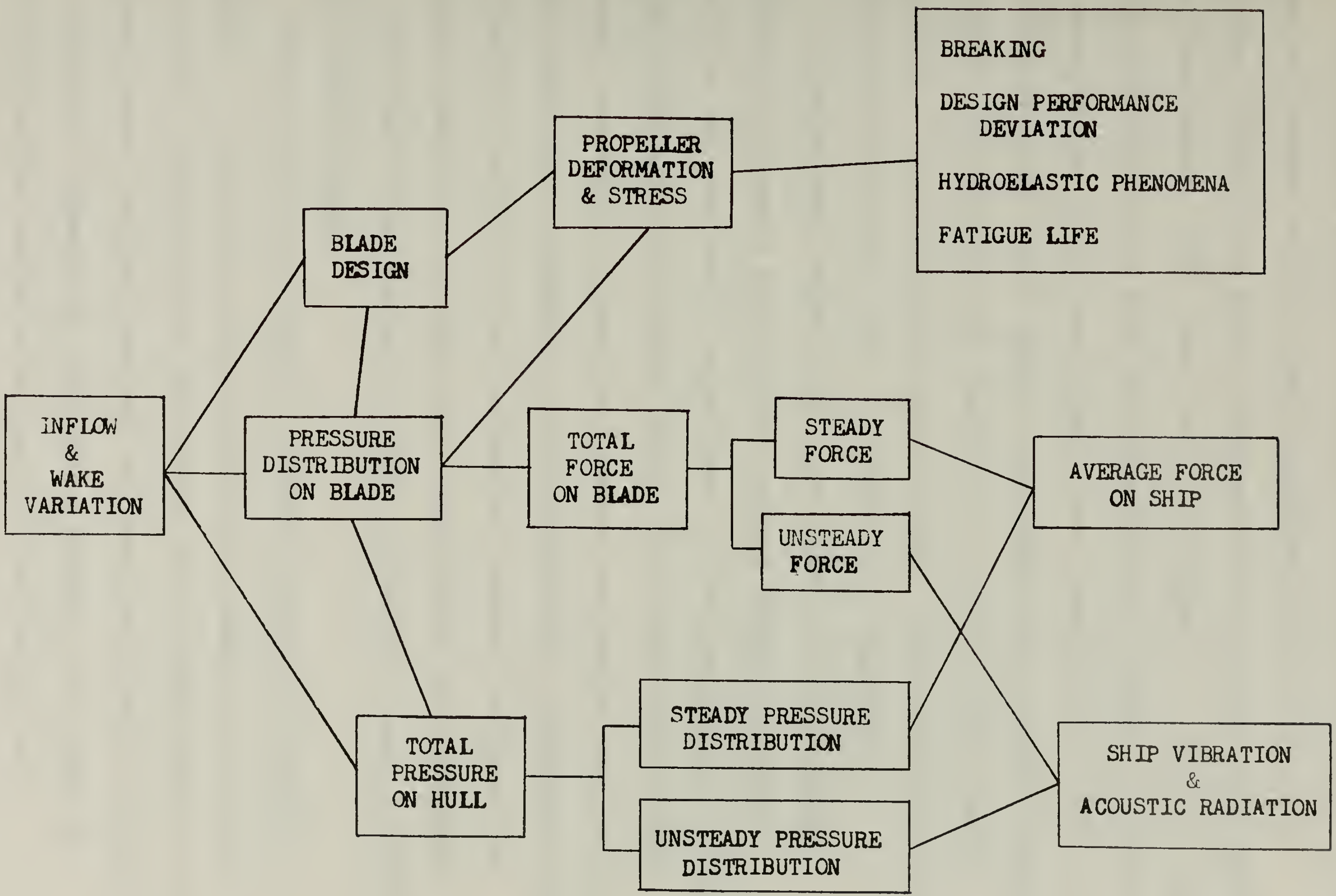

FIGURE I-1. PROPELLER INTERACTIONS

II - BACKGROUND

Wereldsma's success in measuring six components of unsteady propeller forces and his timely appearance at M.I.T. as a Visiting Professor of Naval Architecture and Marine Engineering (April-September 1968) gave rise to a proposal to the National Science Foundation in 1968 by Professor J.E. Kerwin to develop (in association with other things) this capability in the M.I.T. Variable-Pressure Water Tunnel. The Tunnel had recently undergone extensive modification and renovation, and its large, easily accessible (both physically and visually) test section and ideal flow conditions lends itself to capability expansion.

A design team under Professors Kerwin and Wereldsma formulated the basic plan for the sensor design, weighing heavily on the successful experience of the instrument developed at the Netherlands Ship Model Basin. The design was refined through inter-active iteration between the design team and the Draper Laboratory (formerly the Instrumentation Laboratory) who eventually detailed all the mechanical pieces, designed the electronic amplifier package, and constructed the instrument. It was completed in the spring of 1970, including a static calibration of the strain gages.

Horton (5) did a "Holzer Method" torsional vibration analysis of the system, and predicted the modes of vibration and natural frequencies of the system, as he envisioned it would be constructed. He also provided an excellent design history of the mechanical aspects of the general design, the means by which this author was able to continue the design and

construction effort.

Petit [6] provided the design and construction of the data acquisition and analysis interfaces between the sensor, signal averaging equipment, recorder, and M.I.T. Compatible Time Sharing System. He also formulated the basic computer program that is used to arrange the data and harmonically analyze it via Fourier analysis.

This author's contribution was the design and construction of the drive system, speed measurement (including back-fit to the steady force propeller dynamometer), and signal take-off arrangement. Additionally the loose ends of the design effort were put together and the data analysis system was revamped. In this effort, it was mandatory that all portions of the "unsteady" system should be easily interchangeable with the existing "steady" system.

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III - APPARATUS DESCRIPTION

The apparatus employed to conduct the experiment consists of:

a) a wake generator - to insure a circumferentially non-uniform inflow velocity.

b) a wake survey - to determine the characteristics of the inflow in which the test propeller is operating.

c) the "unsteady" propeller dynamometer- to sense the force components.

d) a propeller

e) the signal analysis equipment.

<u>Wake Generator</u>

The wake generator was designed as an arc-segment shape frame into which varying wire and mesh sizes could be placed to achieve different wakes [7]. It was placed only on one side of the shaft in order to produce a once-per-revolution non-uniformity and wide enough (75°) to provide substantial blade loading variation. It was placed upstream one test section diameter (or two - 10" propeller diameters) from the propeller plane, far enough removed so that the pressure field due to propeller loading will have a negligible influence on the velocity distribution produced. This will insure that the inflow measured in the absence of the propeller can be reasonably assumed to be that which exists with the propeller working.

<u>Wake Velocity Survey</u>

A wake velocity survey was conducted in the plane of the propeller with a radially-varying, rotatable single pitot-static

tube arrangement. Static and total head were measured every 10° (5° intervals where drastic velocity variations existed) at 10% radial spacings. A special pitot tube holder was screwed onto the measuring shaft (dynamometer sensor) at the propeller plane and was rotated by hand, external to the test section. Different diameter pitot tubes were obtained so that exact survey corrections for measurements in shear flow could be achieved, as explained in Appendix B. Vortex splitters [8] were attached to the pitot tubes to reduce vibration when measuring at the outer radii and permit full test section survey, as might be needed for larger diameter propellers or different test configurations.

Unsteady Propeller Dynamometer

The "sensor" is mounted at the extreme downstream end of its own propeller driveshaft, to which the propellers are attached. It senses the six components of force by means of strain gages, regular foil gages being used to measure Torque (Q) and Thrust (T), and semiconductor gages to pick up the smaller orthogonal forces (F_x, F_y) and moments (M_x, M_y). These forces are measured with respect to an initially large flywheel which acts as a system mechanical ground. The flywheel is in turn isolated from other exciting forces by the soft bearing mounts and the relatively flexible driveshaft. DC operational amplfiers located physically within the sensor amplify the signals before they are removed via low noise slip rings at the drive end. These slip rings also provide the means by which DC excitation voltage is supplied to the strain gage bridges and amplifier circuits. A rotational reference point is provided by

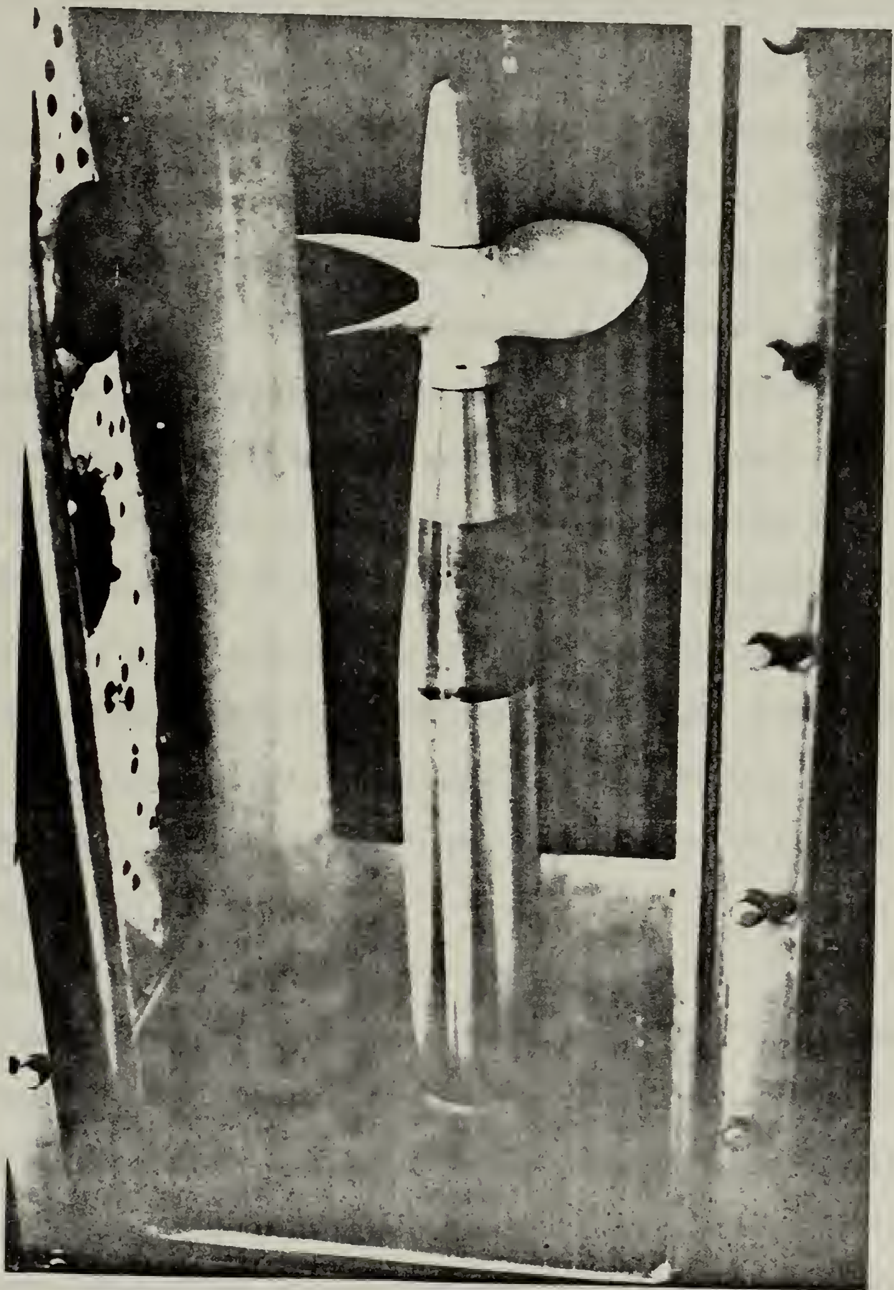

FIGURE III-1. DYNAMOMETER WITH WAKE GENERATOR AND PROPELLER

a rotating photo diode emitter-receiver shining through a stationary slotted disc.

Signal Analysis Equipment

The signal analysis equipment and procedure as proposed by Petit [6] was employed. The six channels of amplified strain gage signals were simultaneously fed into a Northern Scientific (NS-550) Digital Signal Averager where they were CRT viewed and stored in integral memory, after being digitized and averaged. Unfortunately the originally planned M.I.T. Compatible Time Sharing System is being phased out, so slight modifications were made so that the measuring equipment could be used with the CP-67/CMS time sharing system. After communication with the computer was established via data-phone, the stored data in the NS-550 was read into the computer using the associated Teletype printer. A punched tape was simultaneously made for record purposes. Similarly after the signals were harmonically analyzed in the computer, these were printed out on the Teletype and punched tape.

Test Propeller

The propeller tested was a standard small hub aluminum 3 blde outboard motor propeller. The propeller was "off the shelf" except for some small blade shaping and the removal of the rubber "damper" bushing and the substitution of a metal one to adapt the propeller to the sensor, maintaining a metal to metal contact. An aluminum propeller was chosen in order to have a smaller effect on the frequency sensitivity of the sensor.

IV RESULTS AND CONCLUSIONS

Developement Problems

In the early stages of static testing the semiconductor bridges were hampered by excessive amounts of drift. This was eventually traced to the incorrect waterproofing material for immersion in water. In the process to remove the thin vinyl waterproof coating, one of the foil strain gage wires was broken. This necessitated removal and reapplication of all four common Torque and Thrust strain gage backings in order to match the legs within tolerance resistance levels. This illustrates how fragile the force balance is when the strain gage protective cover is removed, even though it is being handled by personnel who normally design and build similar sensitive components. This was even more dramatically demonstrated when it was further damaged in the reapplication of the proper waterproofing compound (Silica Gel).

Static Calibration

Only individual forces were tested due to the inoperability of several force components. No attempt was made to calculate the crosstalk between components, knowing that only initial data was desired. All channels were examined as the individual force load was applied, and no crosstalk was evident during the cursory inspection. The results of the calibration tests were:

a) The Thrust bridge circuit was known to be open (presumably incurred in waterproofing) prior to

calibration and understandibly read zero output.

b) The Torque signal seemed unstable, that is the signal out was obviously not a pure DC one but had random AC superimposed, as viewed on the oscilloscope. The zero loading point, which had approximately a zero output offset, was especially erratic and could easily be affected by the presence of the person taking data. This is indicative of either inductive coupling or a floating ground internal. Once loading proceeded away from the zero point, the drift settled out, but the small AC component persisted. No other signal from a foil strain gage bridge - Thrust - was available for comparison, but the other force signals which were from the semiconductor strain gages, were composed entirely of DC signals, with no flucuation present. With the sensitivity calculated (inch pounds per volt), the system has the capability of measuring up to 1400 in.-lb. of Torque, well above what might be normally expected with model propellers.

The X Force presented a steady stable signal. As noted in Appendix C, the side forces are measured by strain gages in two parallel planes and wired so that the force is measured in axial location independent. Thus the output should have been proportional to the applied load and the distance between the measuring planes, a constant. The static loading was done in three different axial locations and the results (Figure IV-1) plainly show that this force is location dependent. The "virtual"

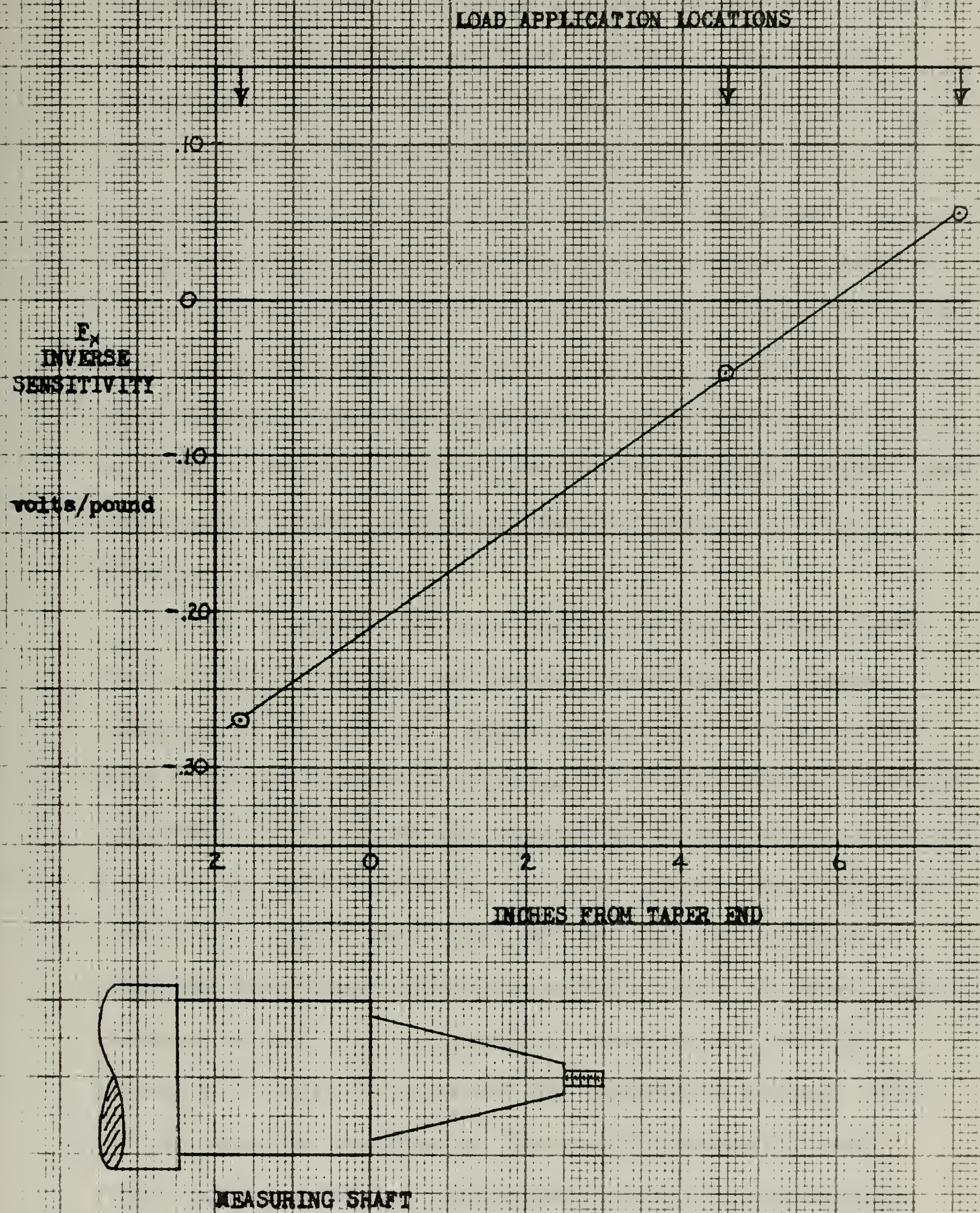

FIGURE IV-1. F_x "VIRTUAL" MEASUREMENT PLANE LOCATION

measurement plane is located out on the measuring shaft taper, relatively distant from either of the actual measurement planes. This indicates that either; i) the gages are not properly wired to the amplifiers, or ii) the input-output slopes (in.-lb./volt) are drastically different in the two measuring planes. In the original strain gages sans amplifiers calibration [14], the load was only applied in one axial location, close to the two gaged planes, thus no conclusion regarding wiring could be drawn. Additionally no conclusion regarding side force measurement range could be reached because of the location dependence.

d) The X Moment output signal was also steady and stable. The "virtual" and actual measurement planes coincide as Figure IV-2 shows. The gain of the signal, even with the external adjustment in the lowest position (shorted), will allow the amplifier to saturate with only a 10-12 lb. side force on the shaft taper, the expected location of the force application. The anticipated unsteady side loads might be on the order of 5% of the average thrust, and a propeller developing 500 lbs. thrust will easily overload the measuring system. This can be cured by quartering the gain internally and removing the external adjustment shorting connection.

e) The Y Force circuit had no output. The strain gage bridge was intact prior to instrument closure, and it is assumed that there is either an open in the amplifier

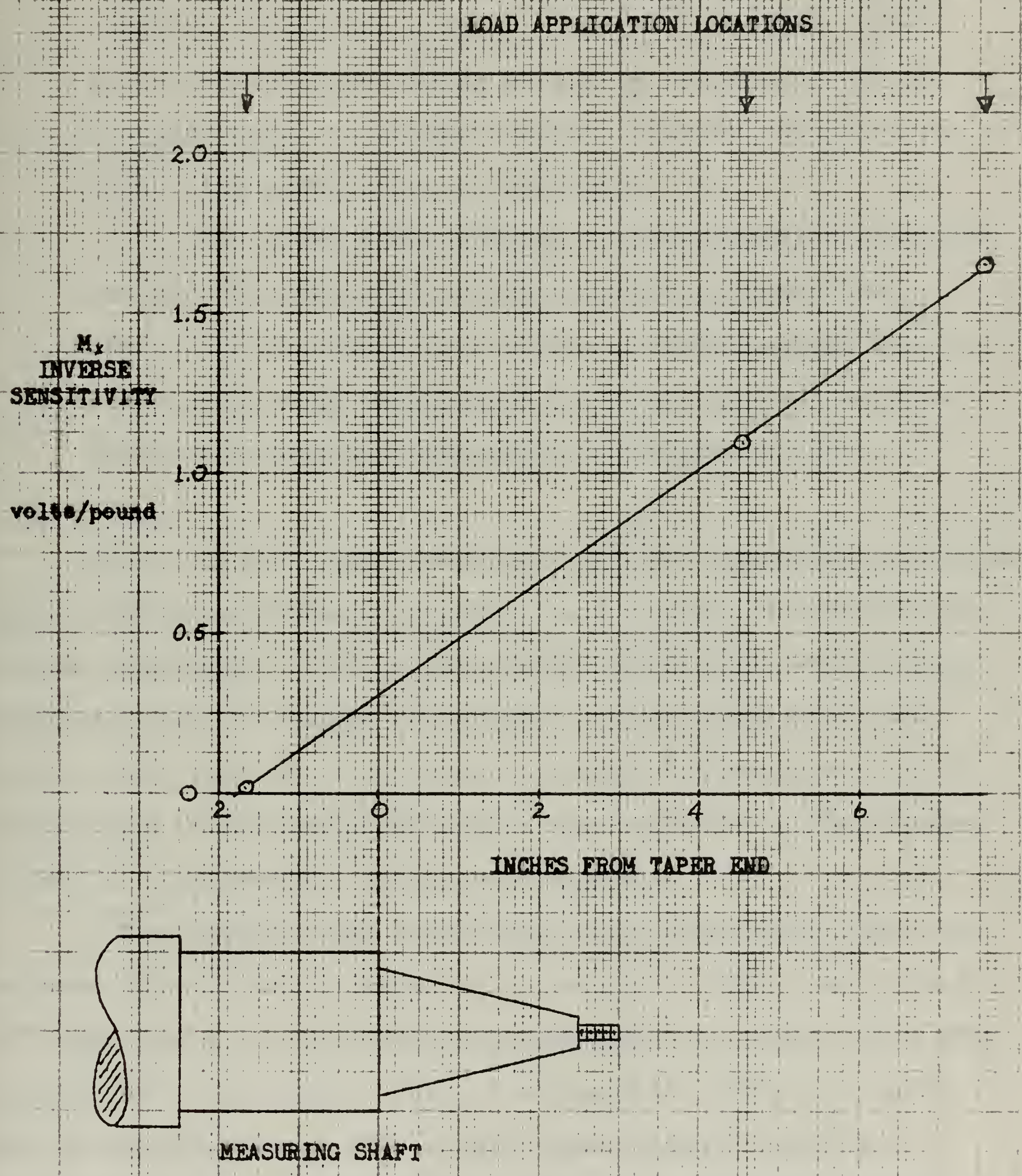

FIGURE IV-2. M_x "VIRTUAL" MEASUREMENT PLANE LOCATION

circuit, or the amplifier is inoperative.

f) The Y Moment amplifier was saturated in the positive direction. A 60 lb. applied force in either direction could not bring it out of saturation. It is presumed that the bridge nulling resistor installed was either the wrong value or defective.

g) The photo-diode emitter in the Trigger circuit was excited with 62ma and operated properly. There was a steady +5 volt signal out of the photofet except when the slit in the disk was rotated to a position between the source and receiver, whereupon it dropped to zero.

With only two force component circuits partially operating and a third describing an unknown-force moment, it was decided to run the system to gain operational experience, and pinpoint problem areas for future refinement. It was hoped that some torque data might be taken since this did not require angular resolution. Additionally dynamic characteristics of the system could be calculated in torque calibration.

Unfortunately when converting the power supply rack from hook-up wire to more substantial permanent wiring, one of the AC power leads was inadvertently connected to ground. This went undetected in the final stage of preparation. When the system was energized, the +5 volt power supply shorted and the semiconductor strain gages and the photofet trigger receiver fed by this power supply were overloaded and presumably damaged. Additionally the A channel signal input circuit of the

measuring Digital Memory Oscilloscope was damaged. The foil strain gages, excited by the ±15 volt power supply, remained operative, as did all the amplifiers and trigger photo diode emitter.

Dynamic Calibration

In an attempt to salvage what little data could be had, the single operational force circuit (Torque) was fed into a regular oscilloscope and viewed with the internal sweep in a free-running mode. Without the benefit of filtering or signal averaging devices, the Blade Rate motion was clearly visible. The unsteady magnitude seemed to be about 20% (peak to peak) of the average torque value, which was expected. Zero output offset was established at 0 RPM and then propeller speed increased. The DC level of the Torque rose to that expected from the static calibration and steady propeller test results. This was spot checked at 900, 1200 and 1500 RPM with minimum inflow. The zero shifted (visibly jumped) occasionally during the early runs, which might indicate a loose lead. During later runs the DC output level only rose to half of the expected value, and the zero offset moved away from that which was achieved statically.

The output signals of F_x and M_x were displayed and only AC portions were present. It is not known if this was an "amplifiers only" vibratory phenomena or if the semiconductor bridges were operating partially. None of the semiconductor bridges responded to a static load, although there was a DC signal out.

When the Unsteady Force Sensor was removed to check the trigger assembly, water was discovered surrounding the flywheel in the trigger cavity indicating that one or both of the rotary seals at either end had failed. There were traces of sodium nitrite (the tunnel water corrosion control additive) on the trigger housing, indicating that at least the downstream seal had failed to function properly. Pieces of teflon coating worn from the bearing surface during break-in could have caused seal failure. Additionally water was found within the flywheel in the amplifier package cavity. The solid driveshaft and static seals at each end of the flywheel should have prevented this.

At this point it was decided to stop, review and plan the corrections to the problems in the system, and then procced further towards the utility of the procedure developed.

V RECOMMENDATIONS FOR FURTHER IMPLEMENTATION

1) Foremost must be the restoration of the force sensor balance to complete operability. This involves returning the sensor to the Draper Laboratory for complete bridge circuitry and amplifier checks. For any damaged strain gages, BLH is recommended for application. The Thrust bridge was to have been repaired by them in any event at their expense. After any strain gage work, the bridge must be nulled in 80°F water, in order to provide for the least zero shift due to temperature. It is recommended that static recalibration be done before the amplifier package is replaced in the sensor cavity, so that any range changes that are desired can be accomplished. The fewer times that the electronics are pulled in and out of their confined space, the greater will be their chance of escaping damage.

2) The trigger area around the photofet and photo diode emitter must be made waterproof, or the connections completely encapsulated. The amplifier and bridge circuitry cavity inside the flywheel must be absolutely waterproof.

3) Because no Thrust measurements were able to be taken, some doubt exists as to the sufficiency of the axial force isolation (flywheel isolation from external axial forces at the drive end) and natural frequency. This will determine the useable instrument dynamic thrust range and must be resolved before any comparative testing or use can be made of the system. Should additional isolation be necessary, spring

diaphragms are recommended for installation in the driveshaft.

4) Data Analysis is extremely time consuming. Time sharing computer analysis is designed in, but time not allowing, was not made fully operational. For example, teletype line feed advance triggering was a problem recognized by Petit [6] in the Compatible Time Sharing System, and presumably will also be a problem in the CP-67/CMS operation. This however should be a rewiring matter to be accomplished by a teletype technician.

5) one of the first operational tests that should be conducted is the duplication and comparison of some of the NSRDC tests [17]. The propellers used are available on a lend basis and references [7] and [17] contain test procedures and results respectively. These might be compared to the unpublished results of similar tests conducted at Pennsylvania State University.

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APPENDIX A.

WAKE GENERATOR

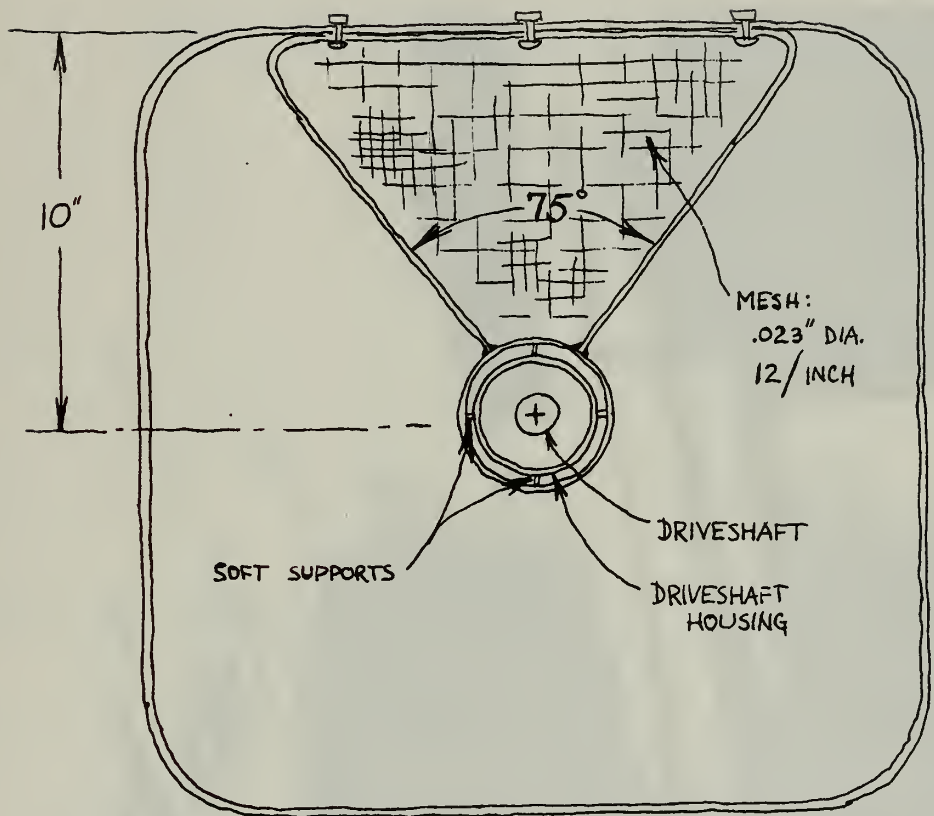


FIGURE A-1. TEST CROSSECTION AT WAKE GENERATOR

The mesh diameter and size was chosen by visually observing the propeller tip vortex pattern distortion as the propeller entered the inflow non-uniformity, in order to produce a significant loading variation. The mesh was wired to the frame so that other sizes might be easily adapted, should a wake modification be desirable.

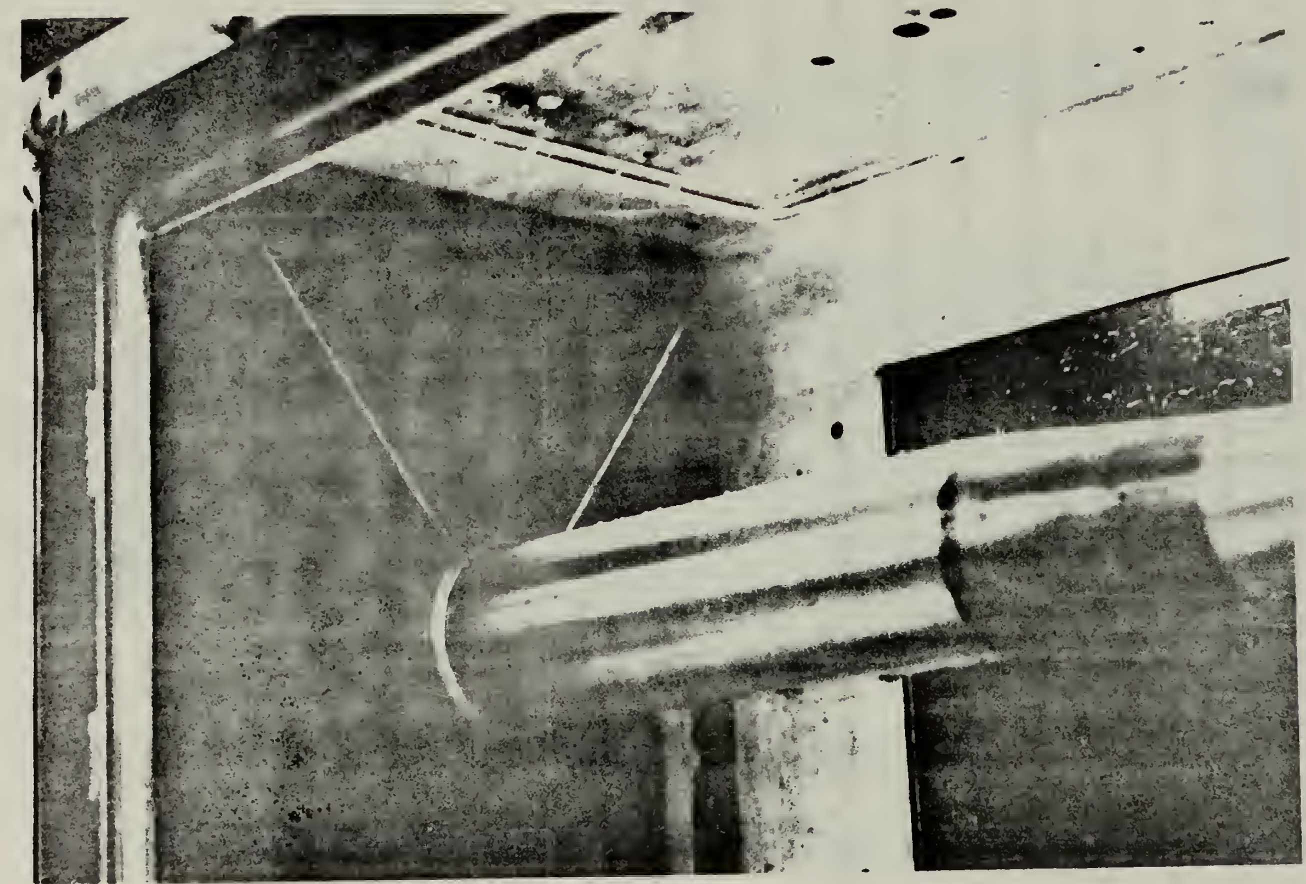


FIGURE A-2. WAKE GENERATOR INSTALLED ON DYNAMOMETR

APPENDIX B

WAKE VELOCITY SURVEY

The pitot-static survey device adapts to the sensor in place of the propeller as shown in Figure B-1. $\frac{1}{4}$" and $\frac{1}{8}$" diameter pitot-static tubes are interchangeable to accurately determine corrections for measurements in shear velocity flow. The pressure signals are removed downstream through a hollow tube that spans the test section and penetrates the window. These are measured either on the 100" manometer or a pressure transducer and digital voltmeter. The manometer scale range of 100" restricts the apparatus to a maximum pitot-static velocity measurement of 20 ft/sec using Merriam Blue Indicating Fluid (Specific gravity = 1.75).

Survey Correction

Accuracy is necessary in the wake survey because the harmonic content will most likely be a key factor in predicting or analyzing the periodic forces on a propeller [9]. Because of the presence of the pitot tube in the shear flow, there exists a distortion of the velocity flow as measured. Figure B-2 shows this in simple 2-dimensional flow. Lighthill [10] computes the tangential flow velocity (v_t) as induced by the presence of a sphere in shear flow as:

$$v_t = .48\, d_e \frac{dV_z}{dy}$$

or

$$v_t = .48 \frac{d_e}{r} \frac{dV_z}{d\theta}$$

Young and Maas [11] verified experimentally that in a

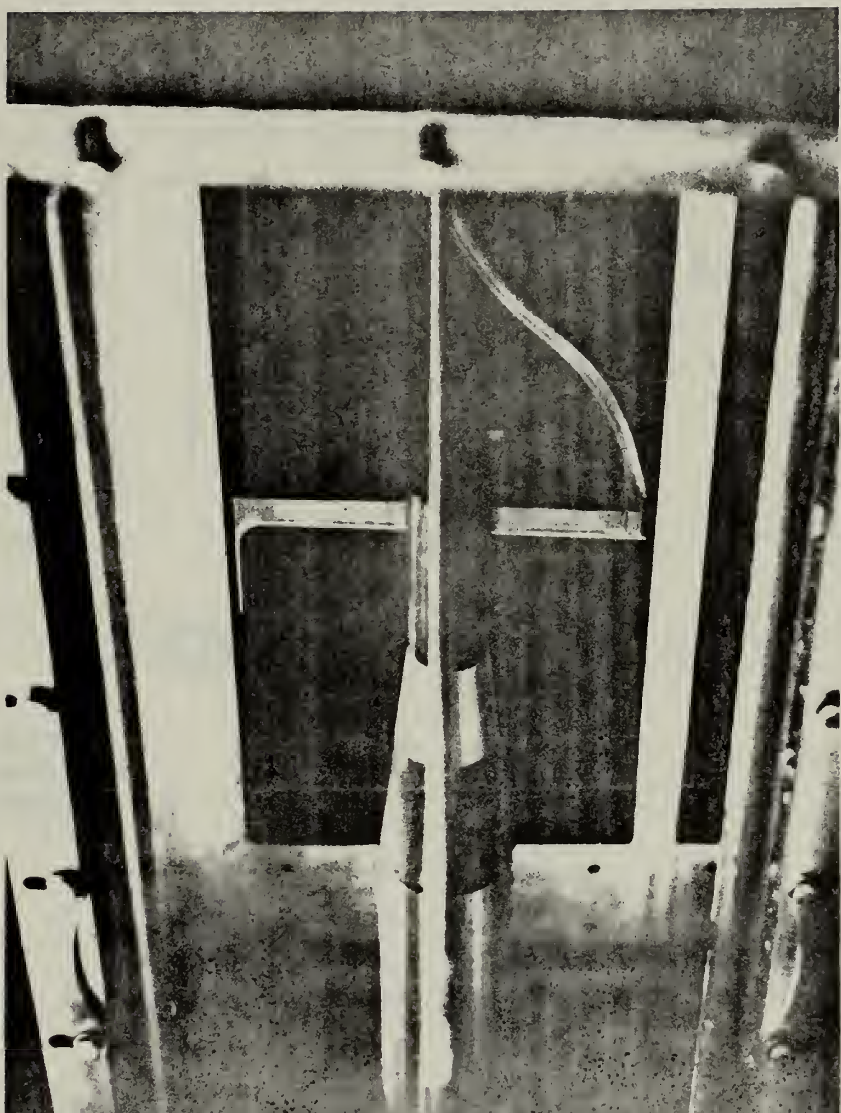


FIGURE B-1. WAKE SURVEY DEVICE

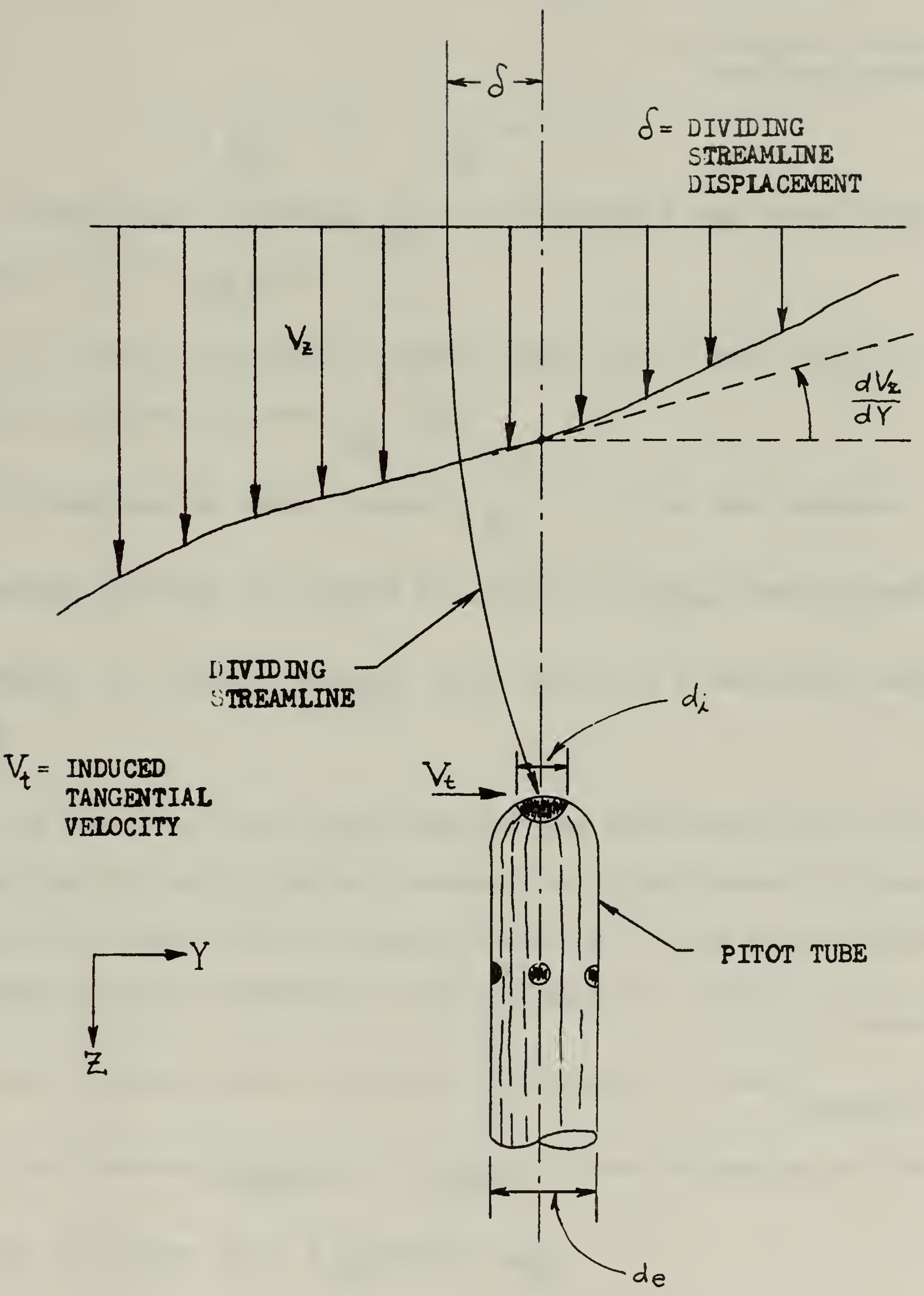


FIGURE B-1. PITOT TUBE IN WAKE SHEAR FLOW

constant pressure gradient, the dividing streamline is displaced a distance where: $\frac{\delta}{d_e} = 0.131 + .082\left(\frac{d_i}{d_e}\right)$ d_e =pitot probe diameter

d_i =total pressure oriface diameter

$$\text{If } \left(\frac{d_i}{d_e}\right) = 0.6 \qquad \frac{\delta}{d_e} = 0.18$$

Macmillan [12] found $\frac{\delta}{d_e} = .15$ and this was reaffirmed by Livesey [13] if $\left(\frac{d_i}{d_e}\right) = 0.6$.

All the pitot-static probes used are of the modified Prandth type which have $\frac{d_i}{d_e} = 0.5$

Therefore we might expect $\frac{\delta}{d_e} = .17$, or the angular correction as seen in Figure B-3 is $\Delta\theta = .17 \frac{d_e}{r}$ always toward the region of higher velocity when there is a non-zero value of $\frac{dV_z}{d\theta}$.

We can see that theoretically and experimentally the correction for pitot probe presence is proportional to the diameter of the pitot tube and inversely to the swept radius. Defining Angular correction $\Delta\theta = \left[\theta \text{ uncorr} - \theta \text{ corr}\right]_{V_z \text{ const.}}$

and Velocity correction $\Delta V = \left[V_z \text{ uncorr} - V_z \text{ corr}\right]_{\theta \text{ const.}}$

and if we assume $\frac{dV_z \text{ uncorr}}{d\theta} = \frac{dV_z \text{ corr}}{d\theta}$ then referring to the blow-up in Figure B-3 $\frac{dV_z \text{ uncorr}}{d\theta} = \frac{\Delta V}{\Delta\theta}$

and

$$\Delta V = .18 \frac{d_e}{r} \operatorname{sgn}\left(\frac{dV_z \text{ uncorr}}{d\theta}\right) \frac{dV_z \text{ uncorr}}{d\theta}$$

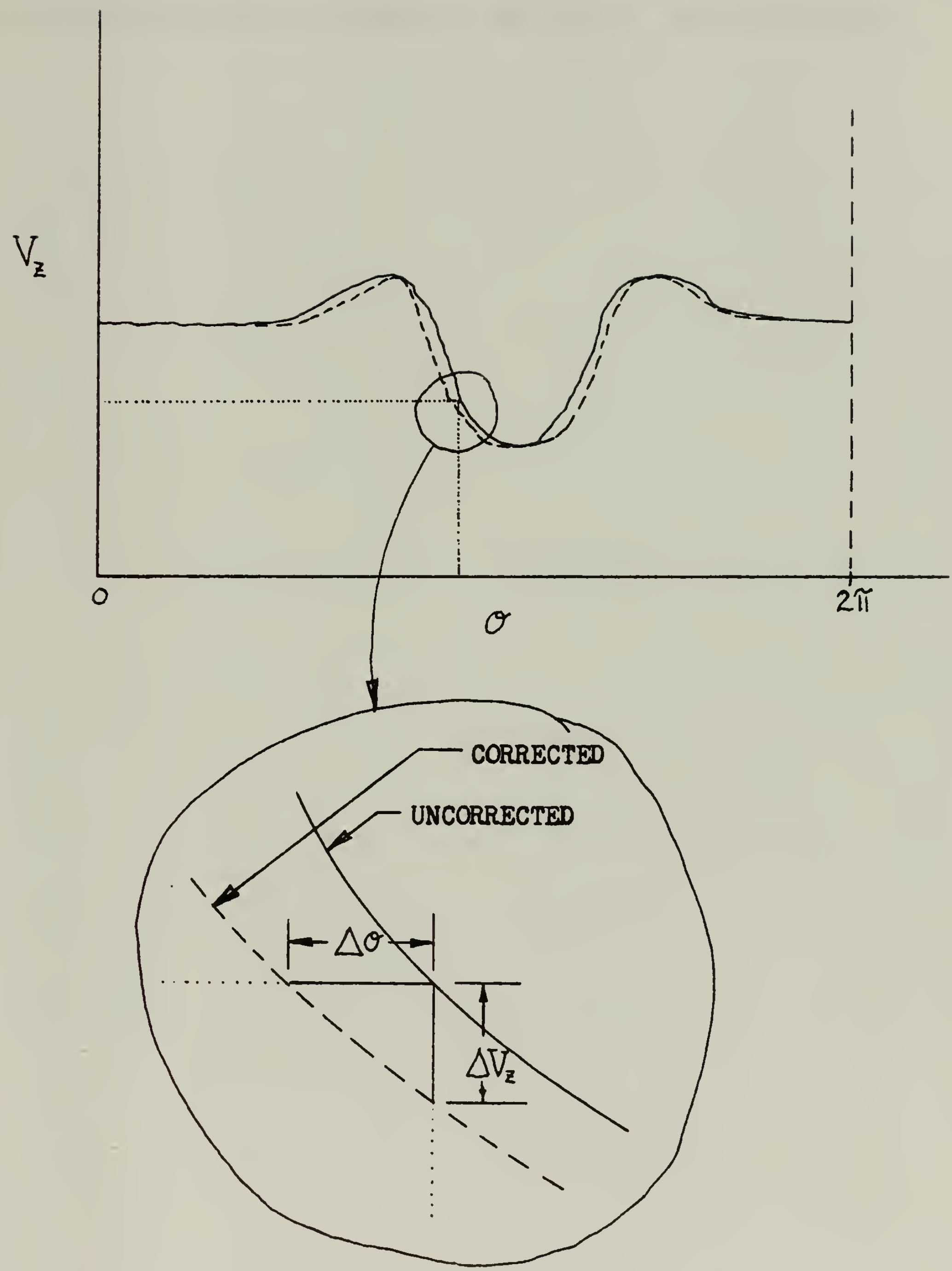


FIGURE B-3. CORRECTION FOR PITOT TUBE PRESENCE

$$\Delta\theta = .18 \frac{d_e}{r} \operatorname{sgn}\left(\frac{dV_t \text{ uncorr}}{d\theta}\right)$$

This can be verified by using different diameter pitot tubes and extrapolating linearly to one of zero diameter.

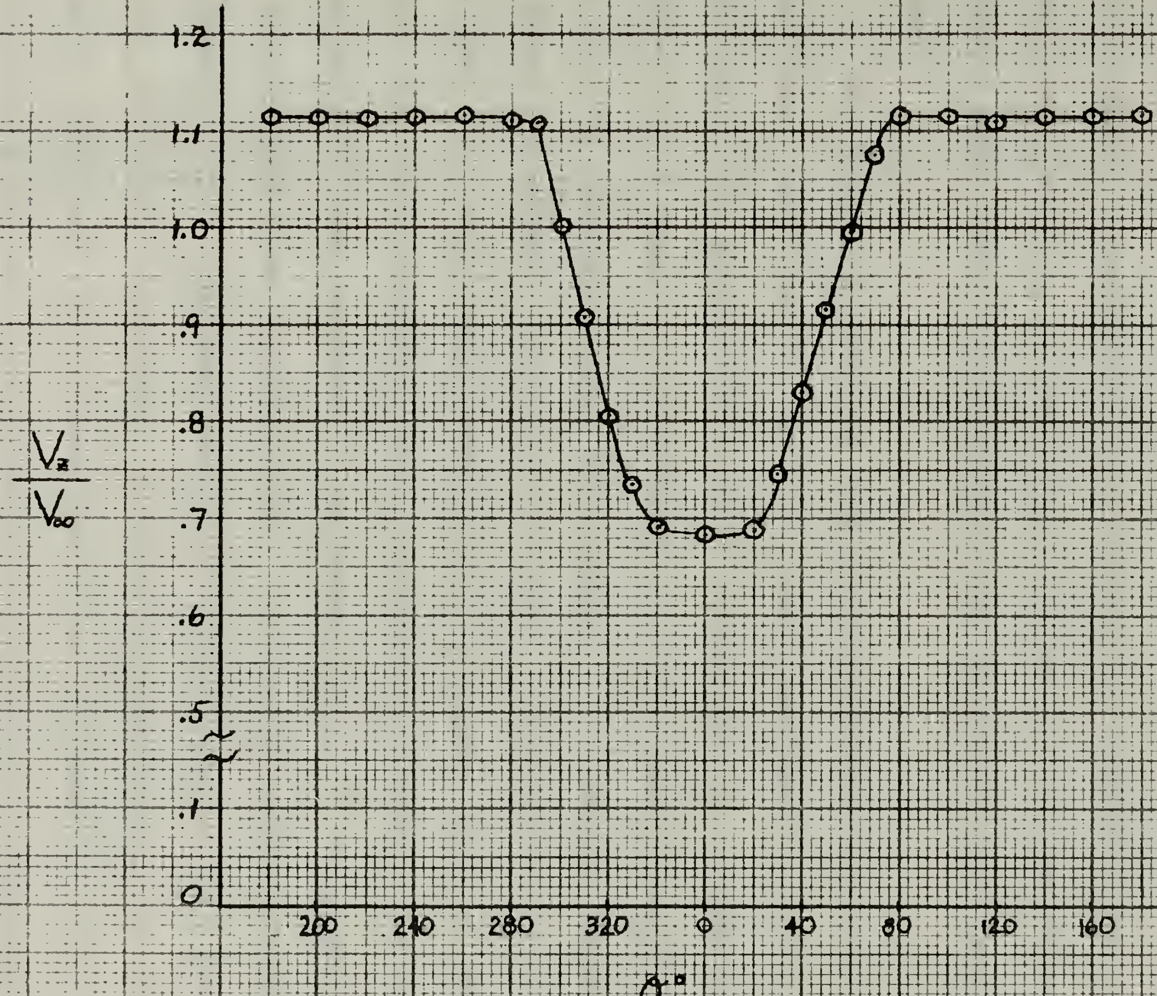


FIGURE B-4. WAKE SURVEY RESULTS (r/R = .7)

UNSTEADY PROPELLER DYNAMOMETER

The two component Steady Force Propeller Dynamometer and the six component unsteady Dynamometer are very similar in appearance (figure C-1). Both are interchangeable for use in the Variable Pressure Water Tunnel, but having limited axial travel, the Unsteady Dynamometer is designed to operate mainly in the downstream portion of the Test Section so that different and varying wake producing appartus may be placed upstream of the sensor.

The sensor itself is a hollow machined rolled-forging of stainless steel located at the downstream end of the driveshaft, onto which the propeller, whose forces are to be measurd, is mounted. The sensor is instrumental with strain gages to record the forces sensed. As can be imagined, the sensor would have to be flexible enough to allow the small propeller forces to strain the shaft so that measurements can be taken, but at the same time, must be extremely stiff so as not to have a resonant frequency in the expected frequency range. To this end, in order to accomodate both constraints, the sensor was constructed extremely stiff and semiconductor strain gages (BLH model SPB2-20-35) are used to measure the small side forces and bending moments. Special foil gages (modified BLH models FAED-25-35-59-1 and FAET-25-35-59-1) are arranged in series to measure the larger forces of Torque and Thrust. All the gages are compensated for temperature sensitivity but not the zero drift. The gages are protected by an open end metal cover and are subject to ambient tunnel water temperature and pressure, and accordingly are

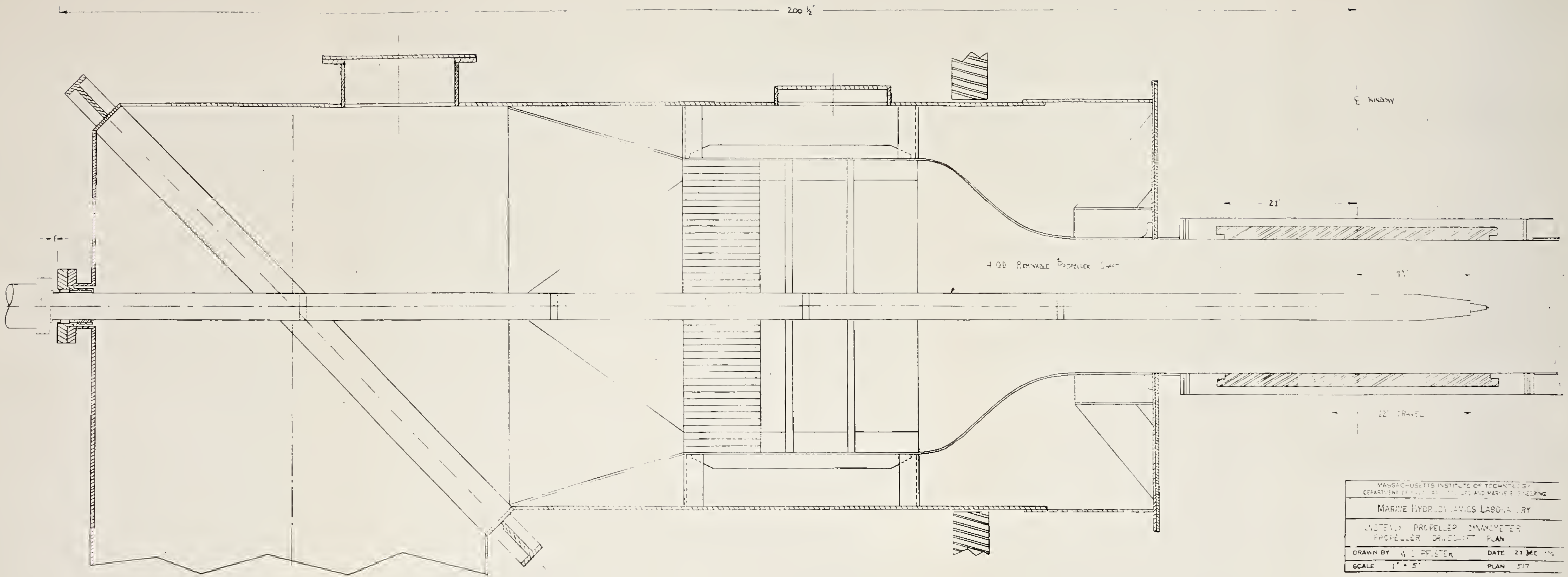
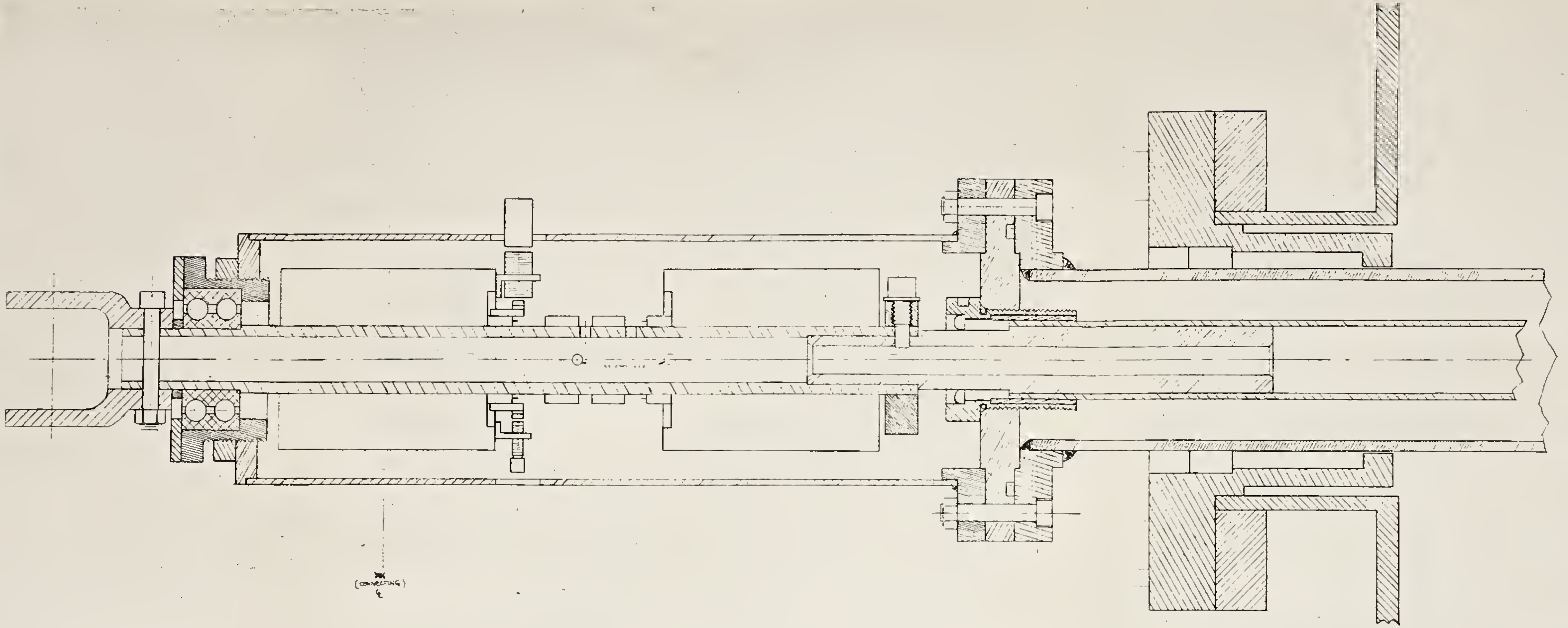

200 ½"
WINDOW
21"
REMOVABLE PROPELLER SHAFT
TRAVEL
DRAWN BY
DATE
SCALE 1" = 5'
PLAN 517

FIGURE C-1.



MASSACHUSETTS INSTITUTE OF TECHNOLOGY DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING	
MARINE HYDRODYNAMICS LABORATORY	
UNSTEADY PROPELLER DYNAMOMETER SLIP RING ASSEMBLY	
DRAWN BY N. C. PFISTER	DATE 6 JAN 1971
SCALE 1" = 1"	PLAN 520

FIGURE C-2.

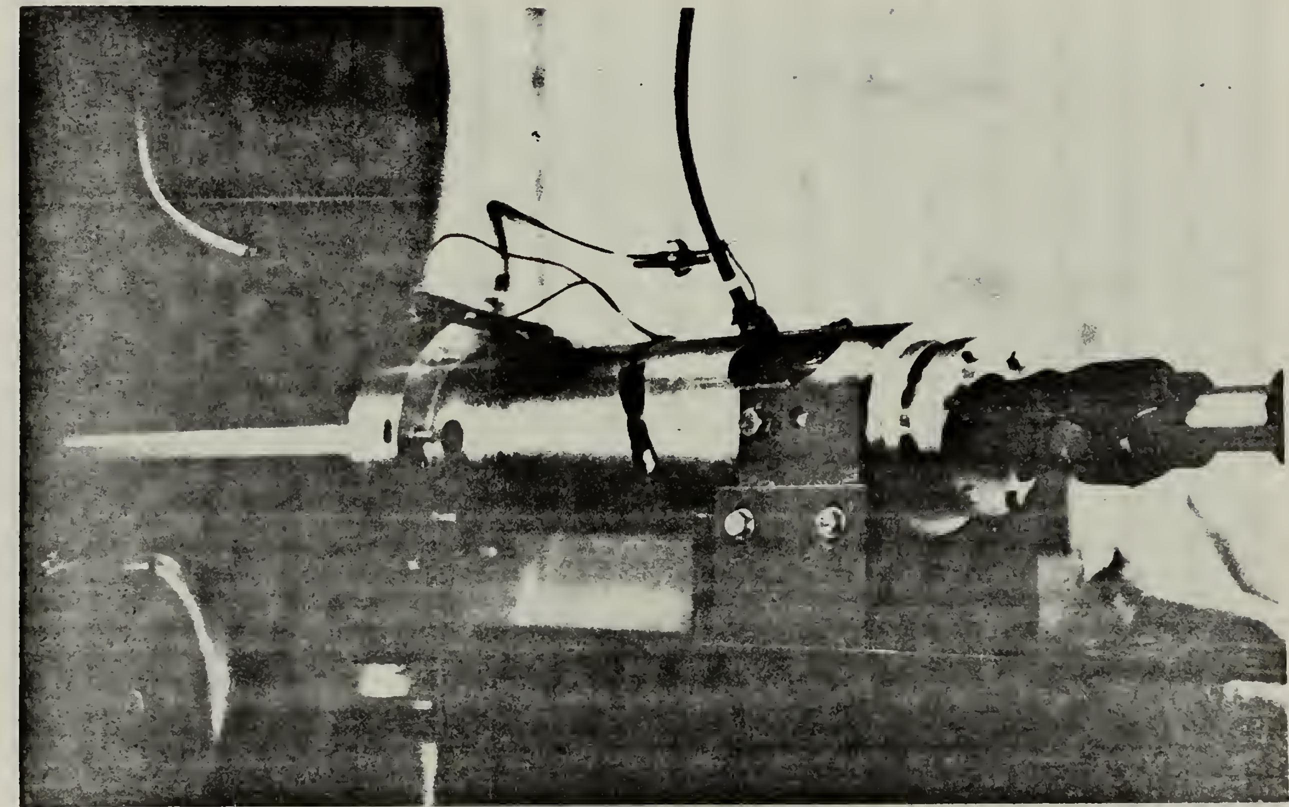


FIGURE C-2a. DYNAMOMETER SLIP RING HOUSING AND DRIVE

semi-permanently waterproofed. Figures C-3 and C-4 show the sensor and strain gage arrangement.

The strain gage signals are amplified by DC operational amplifiers (National Semiconductor LM-308A) having a nominal gain of 2000. These are located physically within the hollowed-out sensor. The DC amplifiers have the desirable capability of being calibrated statically, and have the inherent ability to transmit steady as well as unsteady force signals. Thus, theoretically the Unsteady Dynamometer has the inclusive capability of the Steady Propeller Dynamometer. Unfortunately the zero drift of the combined temperature effects of the water and heat dissipated in the strain gages and amplifiers could not be accurately predicted, and the reading could easily go off scale as the amplifiers saturate. Surely these can be compensated for, but only at the expense and complication of external (non-rotating) variable resistors which necessitates additional slip rings resulting in loss of axial travel.

AC amplifiers only pass that unsteady portion of the propeller forces (which is all that was desired initially) but at the accompanying difficulty in calibrating the sensor dynamically. This is not an impossible task and can be done by either "shakers" of known force, or by decoupling the strain gages from the amplifiers and calibrating both by static methods separately.

The sensor is attached to the flywheel and then to the 18 foot hollow stainless steel driveshaft, through which the signal leads pass (Figure C-2). This in turn is coupled to the

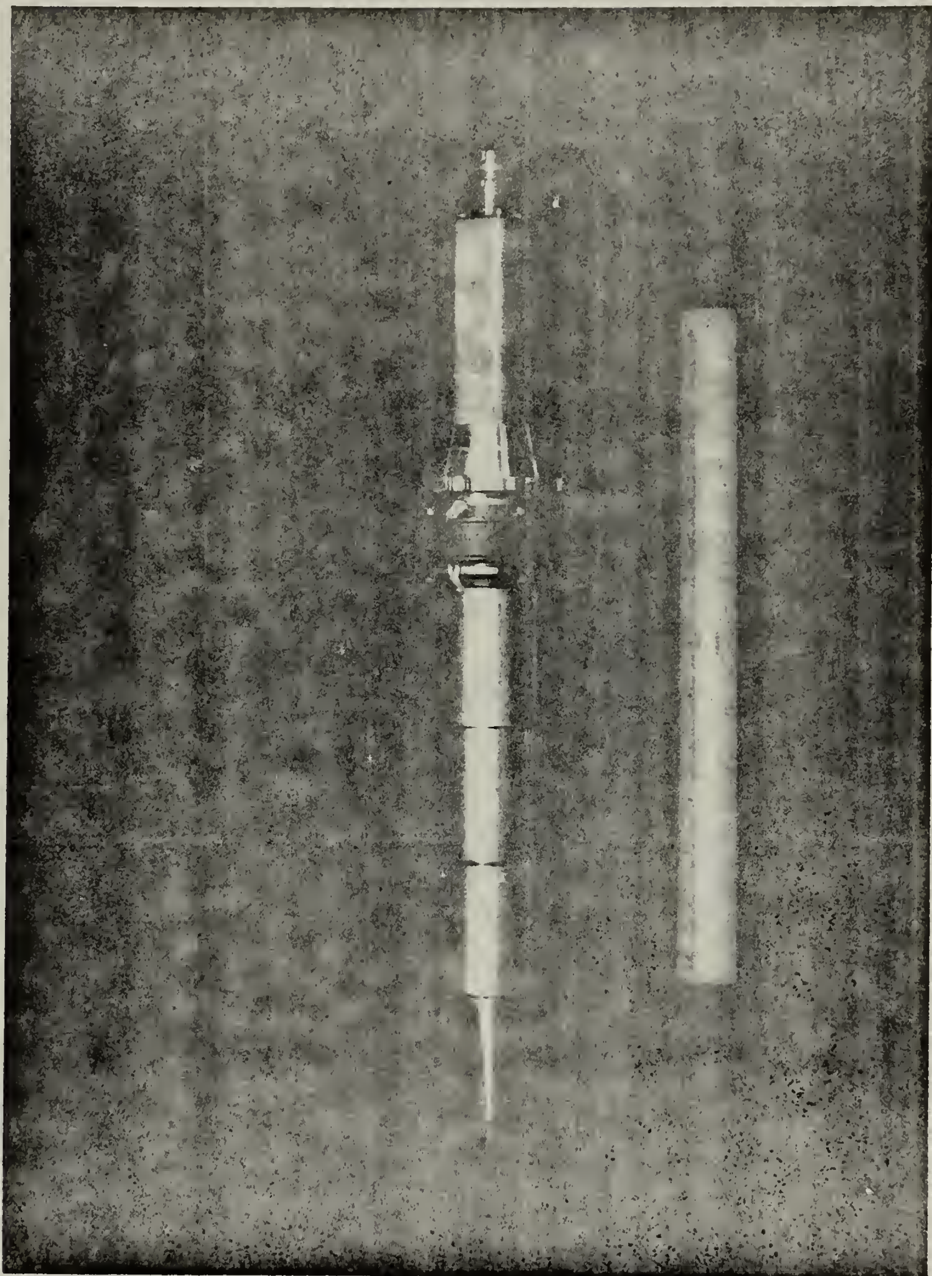


FIGURE C-3. SIX COMPONENT UNSTEADY FORCE SENSOR

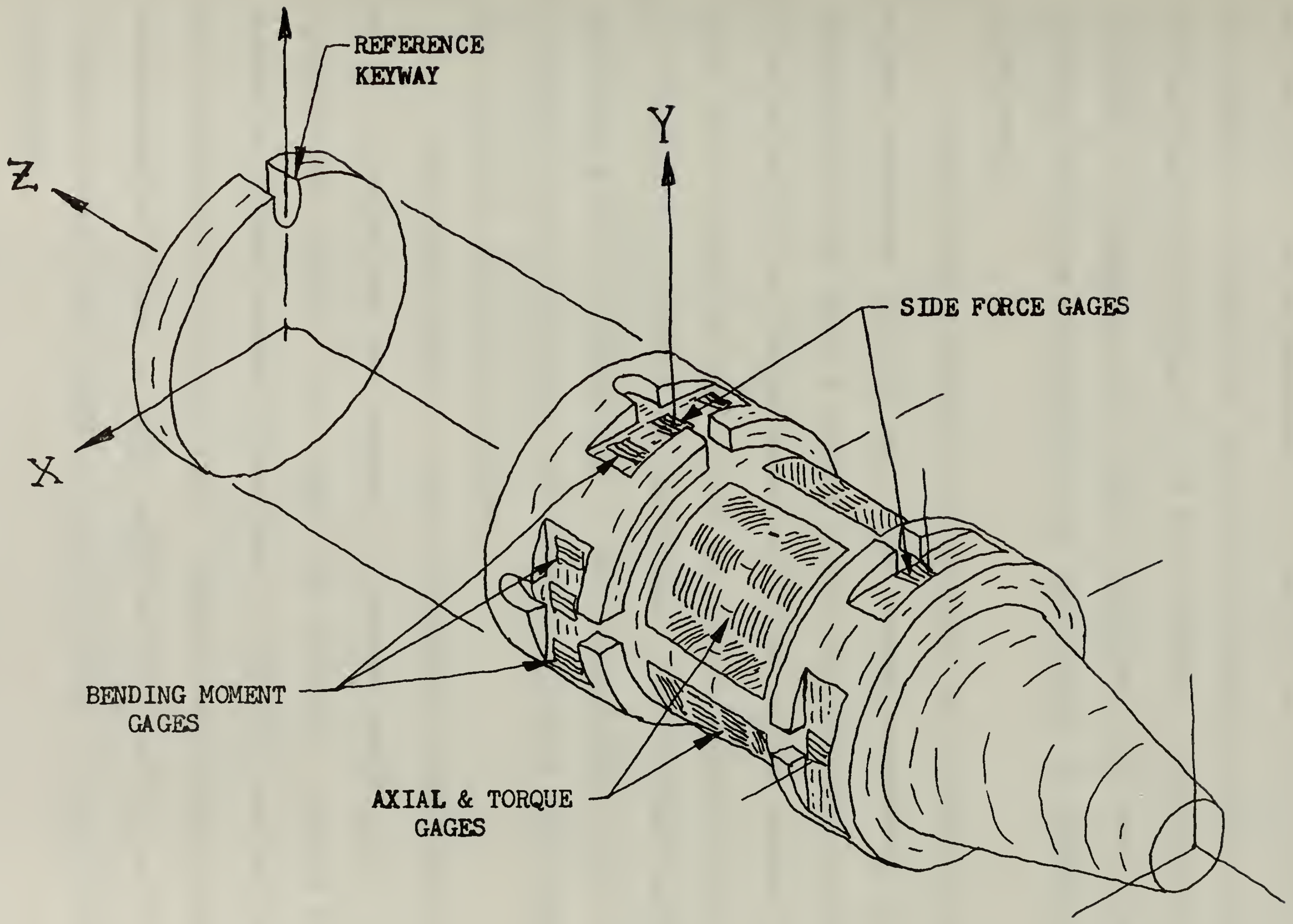


FIGURE C_4. STRAIN GAGE ARRANGEMENT

slip ring shaft and then driven through universal joints via multiple rubber belts by the Propeller Tunnel Ward Leonard type drive motor. Thrust is absorbed at the extreme drive end of the shafting arrangement by double row ball bearings. The driveshaft is supported by gravity-pressure water-lubricated teflon-coated bearings on 39 inch centers. The bearings are located in couplings that screw together with the driveshaft housing over the driveshaft and are sealed to contain the water lubricant.

Rotational reference is provided by a rotating photo diode (Monsanto M1-20C) and light source separated by a stationary disc with a single slit. The photofet is located in line with all the "reference" markings on the sensor, but the disc slit, which is positioned by the driveshaft front cover, is arbitrarily located as the pieces are screwed together. This position must be determined if the measurements are to be resolved into horizontal and vertical forces and moments from the rotating coordinate system.

Rotational speed is very accurately determined by the use of a 60 tooth gear and magnetic pickups reading on a digital counter per minute. This reads RPM directly. Active and passive magnetic pickup elements are used to provide system redundancy and checking, as well as gross (meter) and exact (counter) RPM measurements. Speed is also measured indirectly by the photofet trigger pulses per number of timed sweeps in the data digitizing equipment.

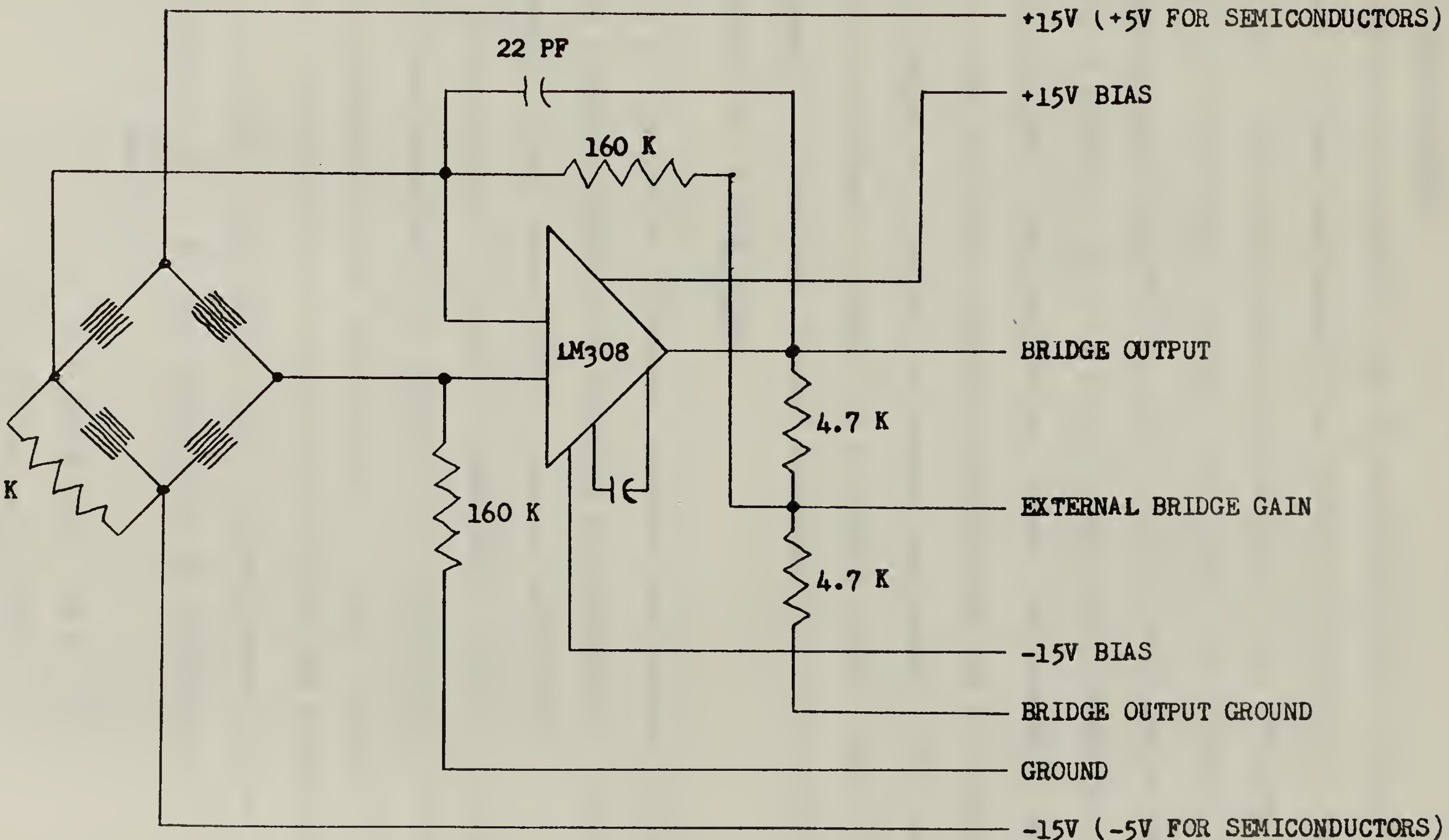


FIGURE C-5. TYPICAL STRAIN GAGE BRIDGE AND AMPLIFIER CIRCUIT

Static Calibration

Before calibration can be underteken the orientation of the axes, forces and moments as shown in Figure C-6 must be understood. Note that what are referred to as bending moments (M_x,M_y) are not moment vectors but rather are moments produced by corresponding forces (F_x,F_y). A positive X force causes a positive X moment. This is done so that any eccentric Thrust can be measured. The transverse forces are measured by strain gages in two parallel planes perpendicular to the propeller axis and the gages so arranged to cancel any moment. The bending moment is measured by gages in a single plane. Then, for example in Figure C-7, vertical thrust eccentricity (e_v) can be easily determined by $e_v = \frac{M_v - z F_v}{T}$

where z is the axial distance between the assumed Force plane and the plane in which the moments are measured. Similarly horizontal thrust eccentricity can be determined.

Additionally it must be remembered that all forces and moments are measured with respect to a rotating coordinate system, denoted by the subscripts x, y and z. Most of the time it will be desirable to have these forces and moments in terms of the Vertical, Horizontal and Z coordinates. As can be seen in Figure C-8 if σ is the angle (0 to 2π) between the (+) Y axis and the (+) Vertical:

$$F_V = F_x \sin\sigma + F_y \cos\sigma$$

$$F_H = F_x \cos\sigma - F_y \sin\sigma$$

[illegible]

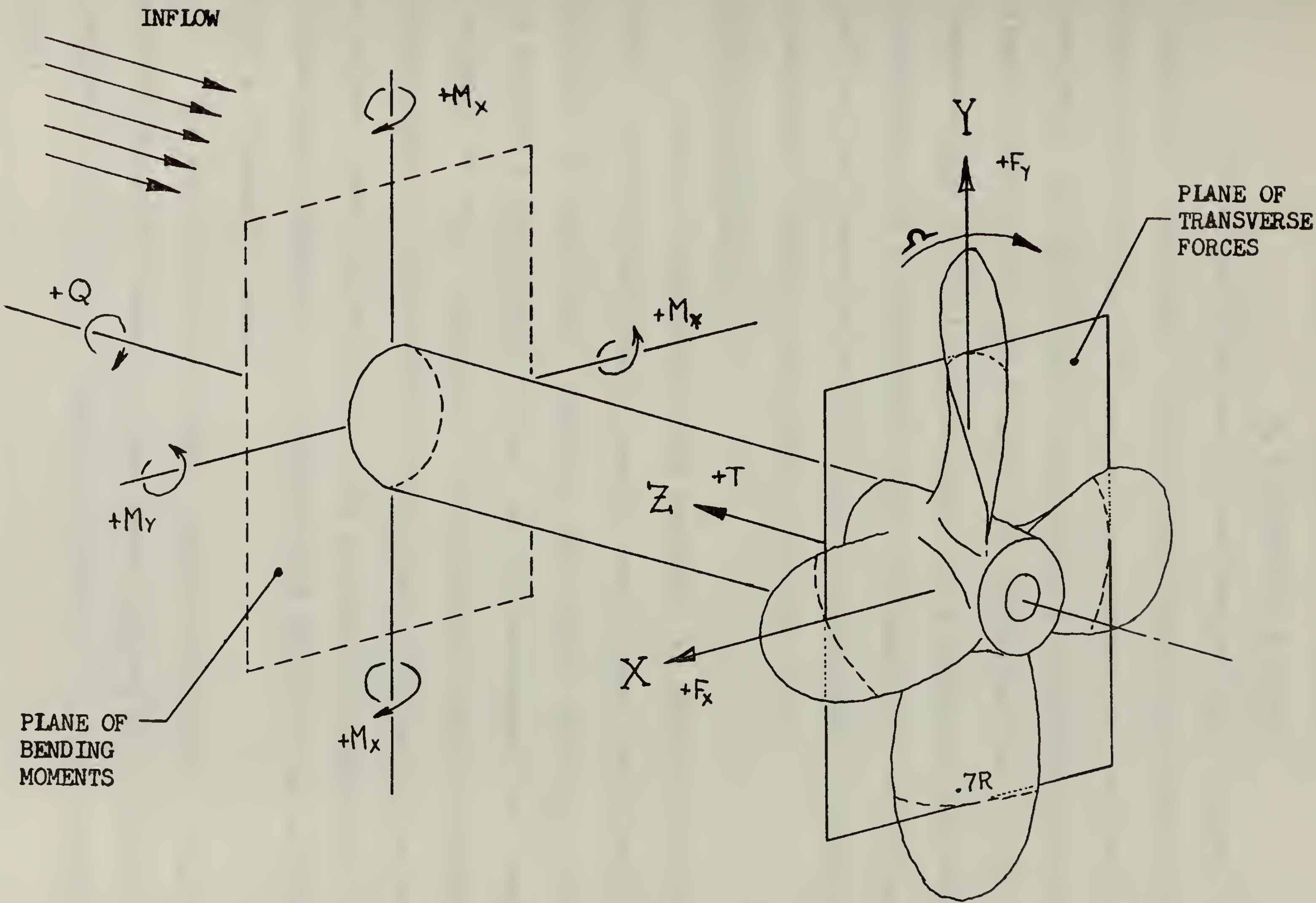


FIGURE C-6. SIX COMPONENTS OF FORCE ACTING ON A PROPELLER

Similarly $M_V = M_X \sin\theta + M_Y \cos\theta$

$M_H = M_X \cos\theta - M_Y \sin\theta$

A static calibration of the strain gage bridges (less amplifiers) was done [14], but new Torque and Thrust gages have been applied since. The static calibration of the entire sensing mechanism was done using the specially constructed calibration stand (Figure C-9) and weights to determine the six by six force-output sensitivity matrix. The purpose of the matrix formulation is to determine gage and amplifier cross-talk, as well as the force to volts-output relationship. These temperature independent results are shown in Figure C-10.

Dynamic Calibration

Several techniques were examined in order to establish a sensor calibration under dynamic conditions. The first and simplest of which was "ringing" the shaft. That is, the shaft is struck a light sharp blow, and by recording the transient response of each component of the sensor gages, a resonant decay curve of the system's mechanical response could be obtained. The limitation of this procedure is that only the fundamental resonance is obtained and there is no calibration over a frequency range.

The next method reviewed involved extensive, complicated systems whereby "known" forces were applied by "shakers" over a frequency band and the response plotted [15]. This method suffers from:

a) Attaching heavy electro-mechanical devices to the tailshaft which involves practical rotational problems

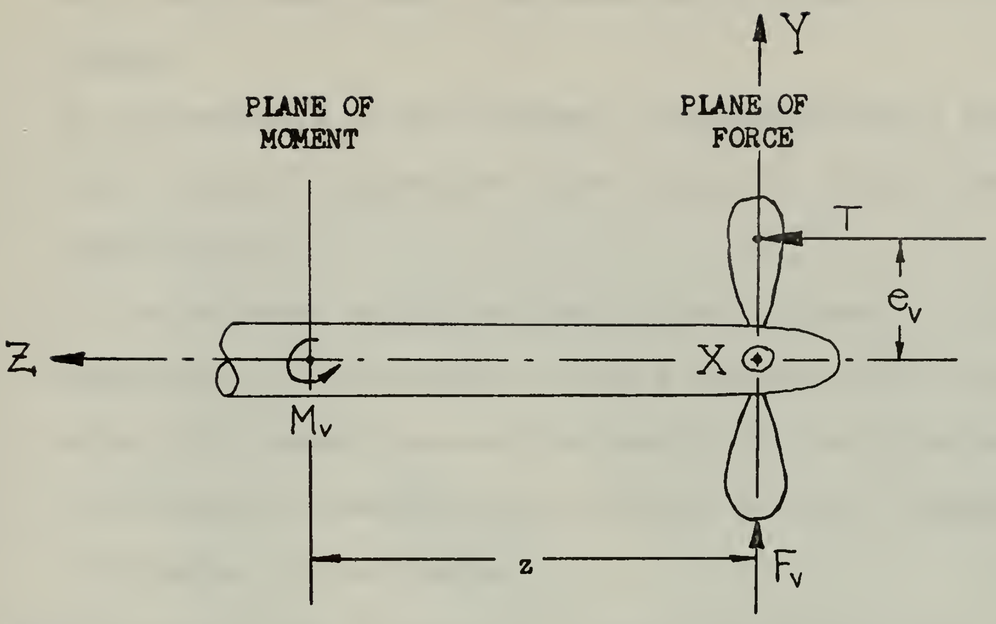


FIGURE C-7. VERTICAL THRUST ECCENTRICITY (σ=0 SHOWN)

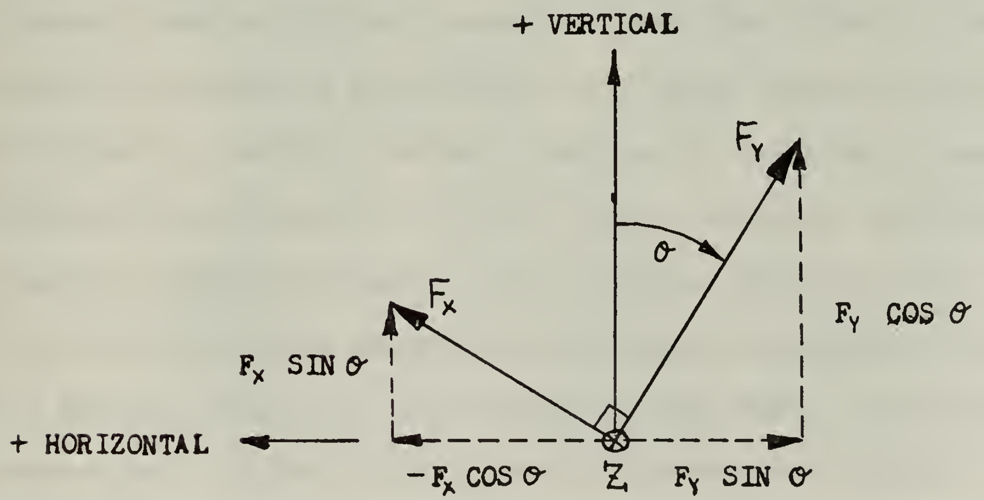


FIGURE C-8. VERTICAL AND HORIZONTAL FORCE RESOLUTION

and significant shaft end mass corrections to the response curves.

b) Uncertainty of the "known" force magnitudes and its own resonant frequencies when modified to suit the application.

c) The unknown actual wetted propeller mass and damping coefficient. Proponents of these methods argue that by using the lumped mass-spring model of the physical balance, the propeller damping only affects dynamic response in the region of resonances.

The complication and expense in time and resources was judged not worth the estimated 10% maximum accuracy that could be achieved by employment of these devices. This is reinforced when we see that the calibrations indicated that the maximum interactions between the loading components was about 3% [16].

The method of dynamic calibration chosen includes the viscous damping of the propeller and its effect is not separated from the system. A calibration run must be done for each different propeller tested. The run is done at a constant Advance Coefficient (J) value, while varying the RPM over the usuable instrument range. Any Reynolds effects will be neglected. The unsteady force magnitude obtained is non-dimensionalized on the steady force at that corresponding RPM. and then plotted versus RPM (Figure C-11). In this manner the usuable "flat" region of the sensor can be obtained.

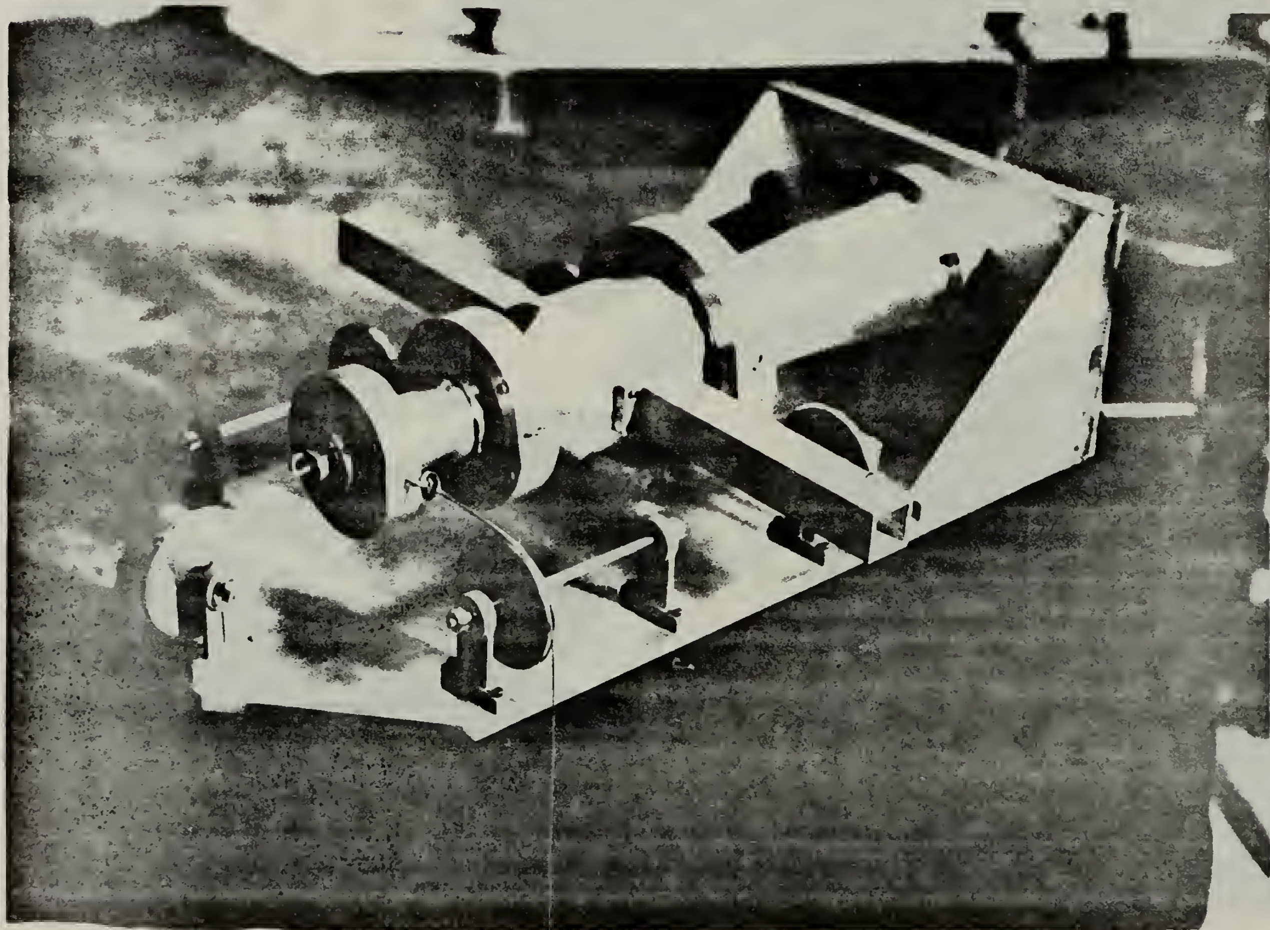


FIGURE C-9. STATIC CALIBRATION STAND (FRONT)

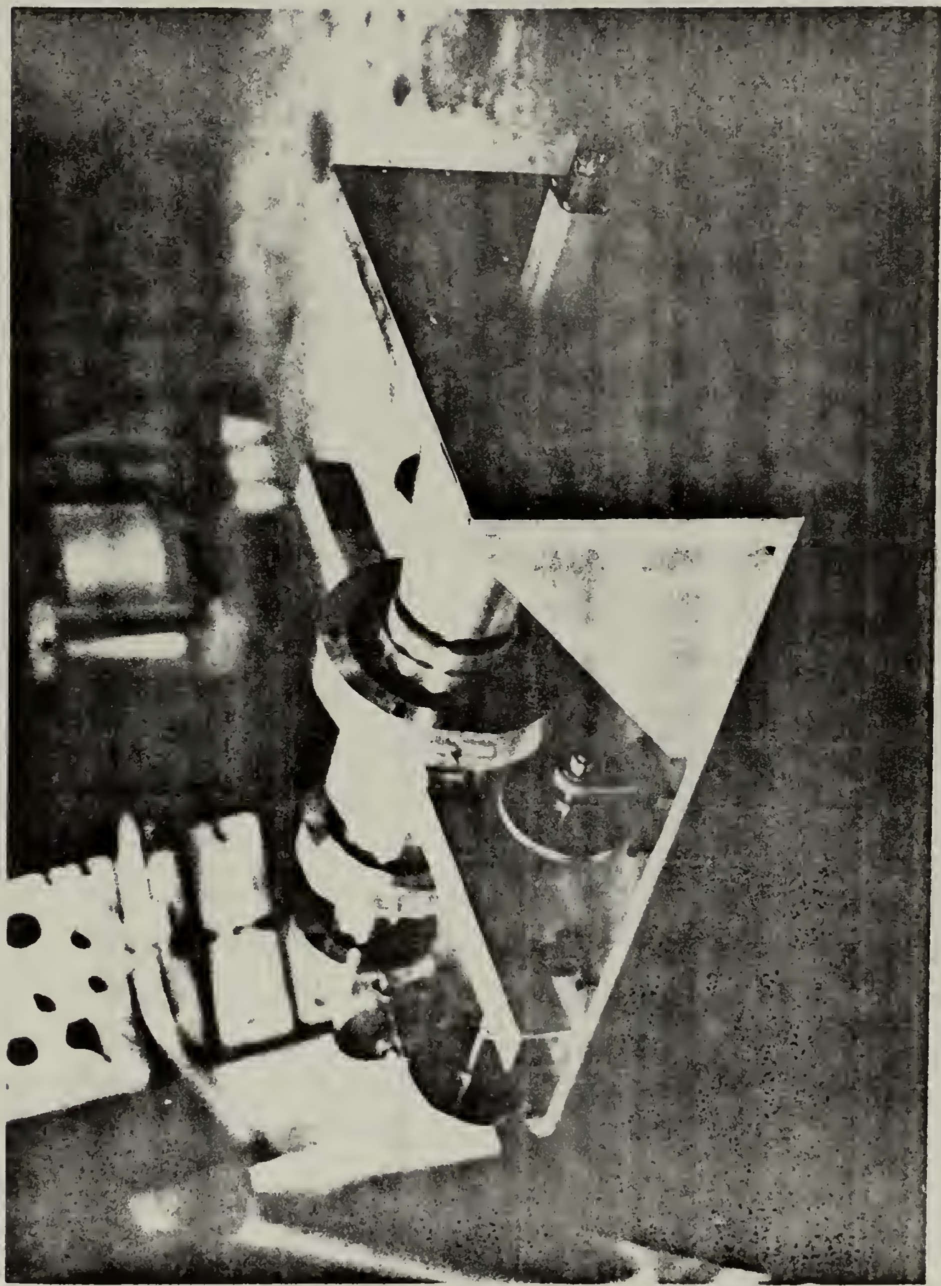


FIGURE C-9a. STATIC CALIBRATION STAND (REAR)

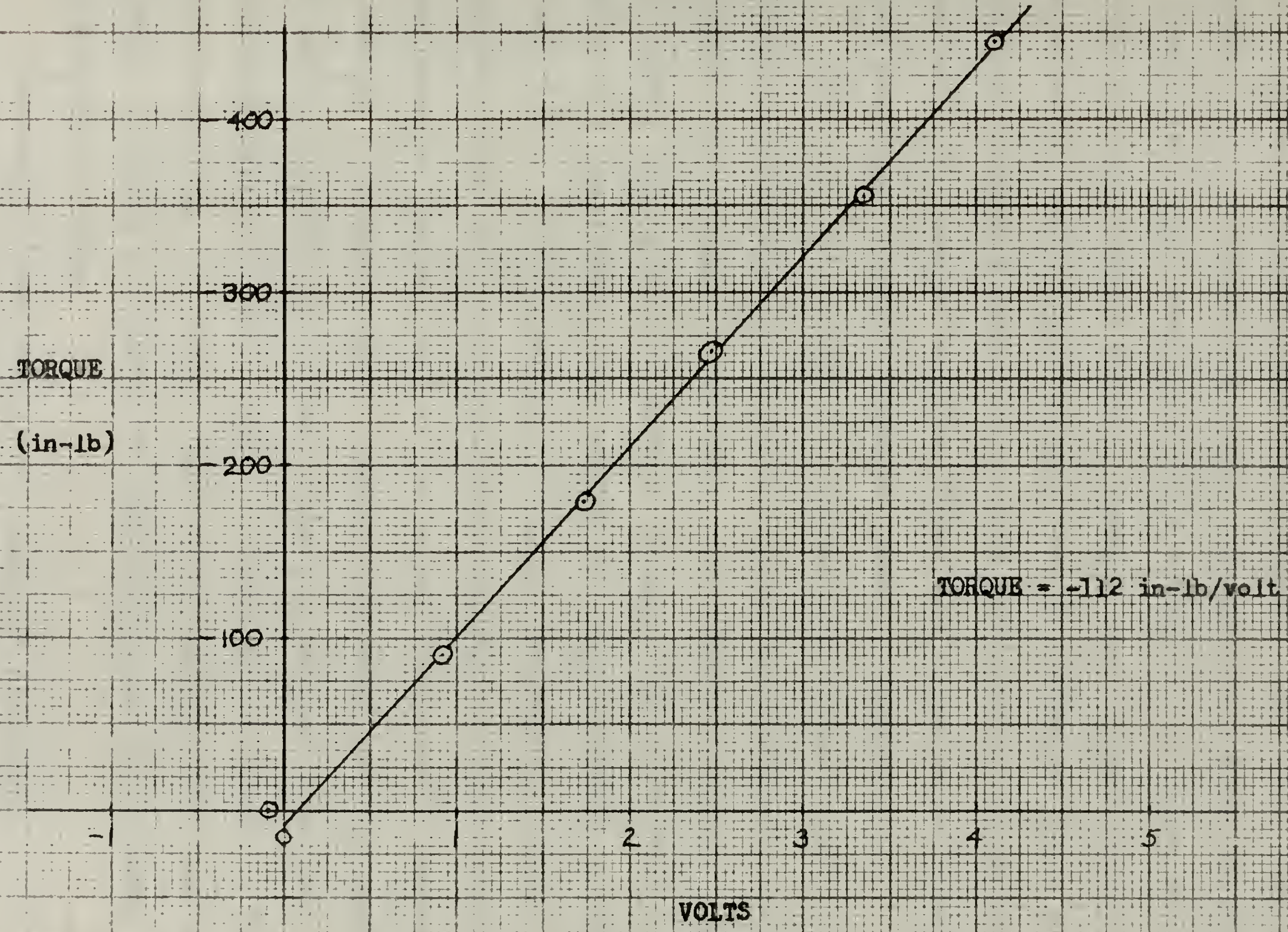


FIGURE C-10. STATIC TORQUE CALIBRATION

APPENDIX D.

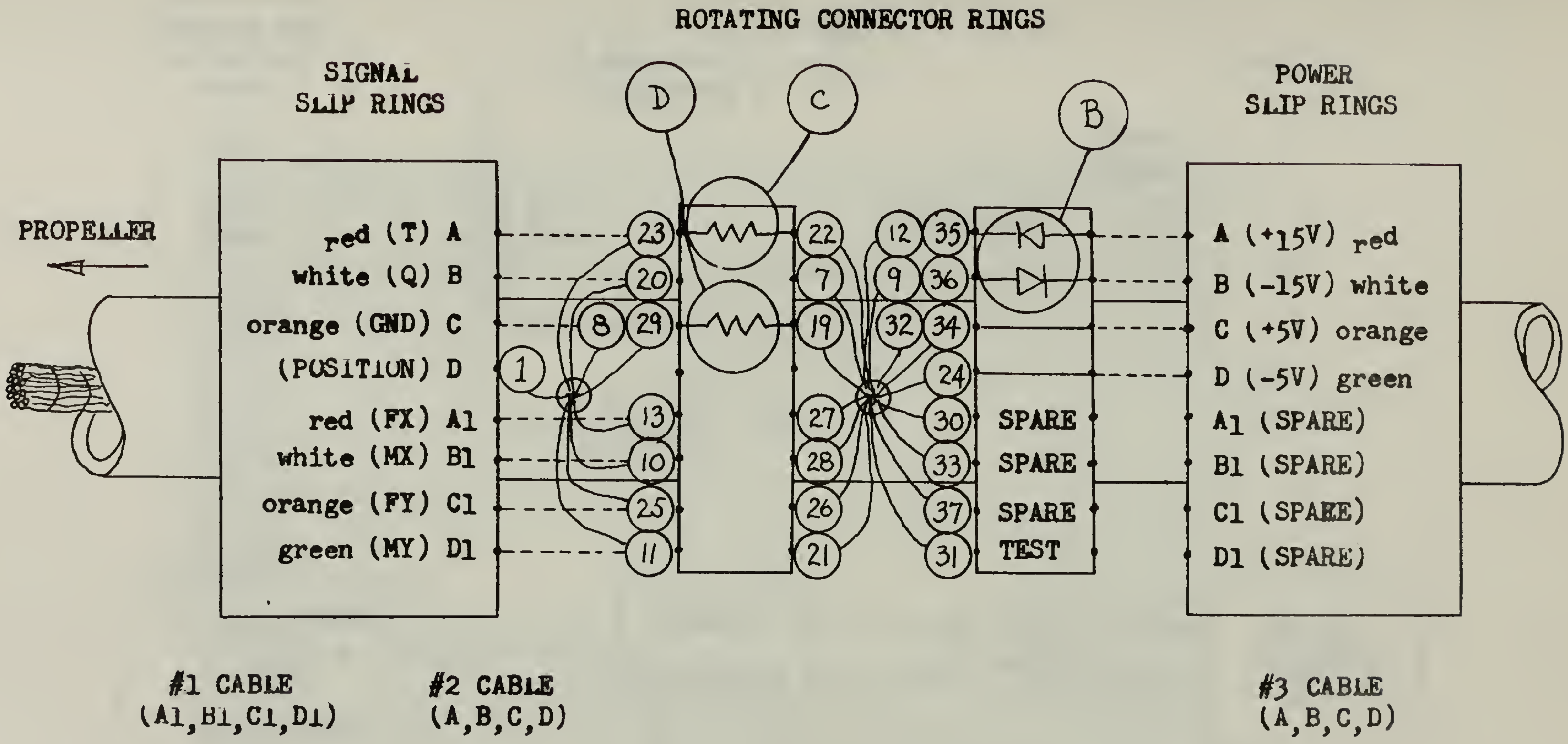
MEASUREMENT AND ANALYSIS EQUIPMENT

After the sensor signals have been amplified they are routed via a 37 conductor cable through the hollow driveshaft to the slip rings. The slip rings bring the DC power excitation in to, and the sensor signals, ground and trigger pulse out of the rotating shaft. Also within the 37 conductor cable are amplifier trimming leads (to reduce the gain by as much as one-half) and several spares. These are attached to connectors which serve as rotating terminal boards (Figure D-1).

From the slip rings the signal and trigger leads go to a Northern Scientific 550 Digital Memory Oscilloscope. Here the signals are digitized, averaged, and stored in memory. Any of the signal inputs or the memory contents can be viewed on the CRT of the instrument. The NS-550 has been modified to take either 1,2,4, or 8 channels of input. The memory capacity is 1024 locations that are allocated according to the number of simultaneous inputs. Thus if we select 8 inputs (6 components of force, 1 trigger pulse, 1 empty) we could have as many as 128 points per 360 propeller cycle per channel recorded simultaneously. If more detail is desired, in order to resolve higher harmonics, a single input could be analyzed each time, thereby allowing a maximum of 1024 points to be recorded per 360 propeller cycle.

Eventually when the minor bugs are eliminated, the stored data will be transmitted via Teletype (Model 33ASTRC) and the Data Phone interface to the CP67/CMS time sharing system

(Figure D-2). Initially, though, the stored data in the NS-550 was punched onto paper tape simultaneously as it was read out of memory by the Teletype, converted to card form, and then batch processed in the IBM 360 to obtain a harmonic analysis.



NOTES:
A) ENCIRCLED NUMBERS REFER TO DRAPER LAB DWNG. #177274.
B) PROVIDE AMPLIFIER PROTECTION AGAINST POWER REVERSAL.
C) EXTERNAL GAIN ADJUST.
D) CONTROL PHOTO-DIODE CURRENT.

——— 37 PIN CONNECTOR WIRES

------ CONNECTOR RING TO SLIP RING

FIGURE D-1. SLIP RING WIRING DIAGRAM

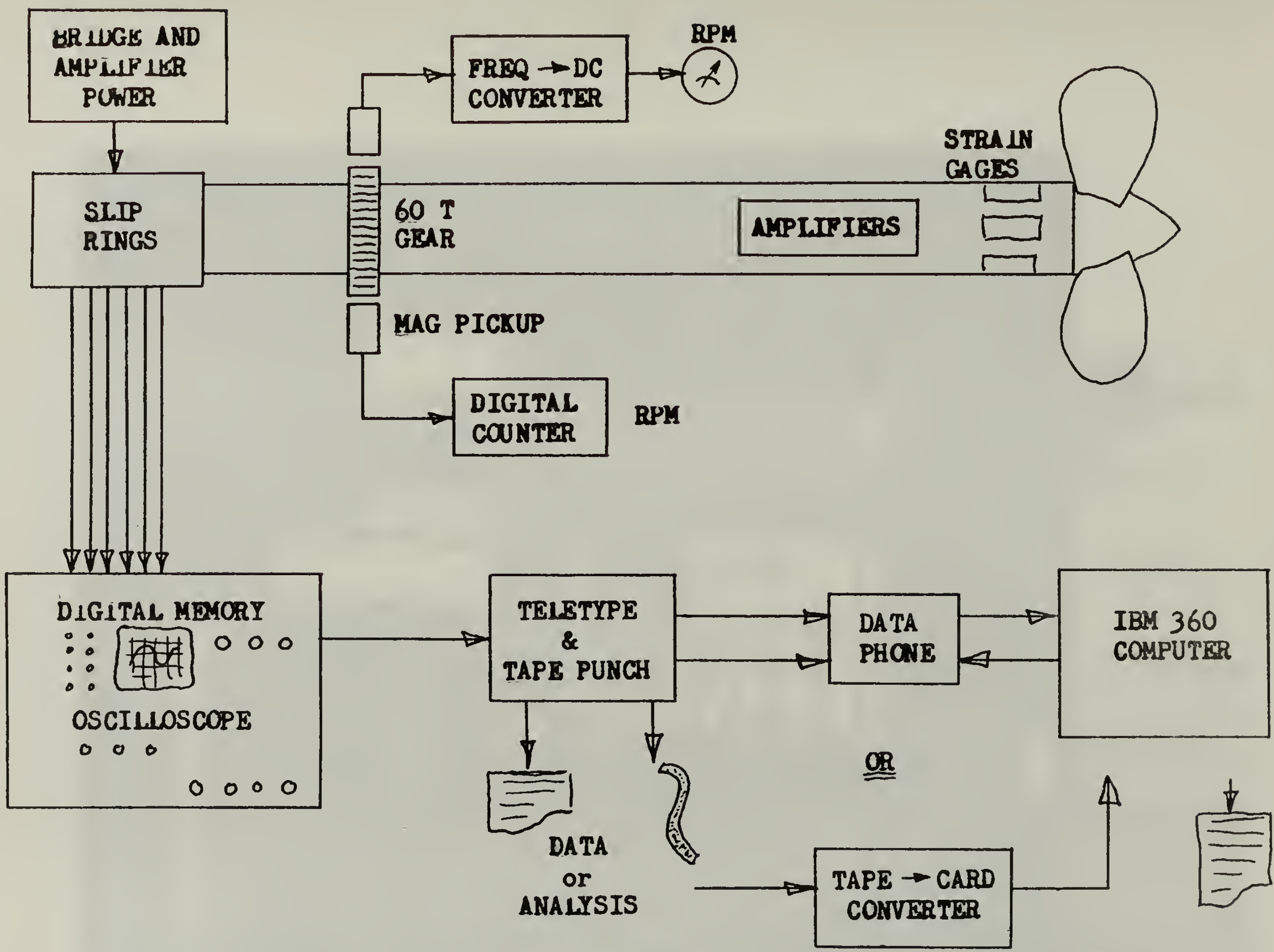


FIGURE D-2. SIGNAL ROUTING

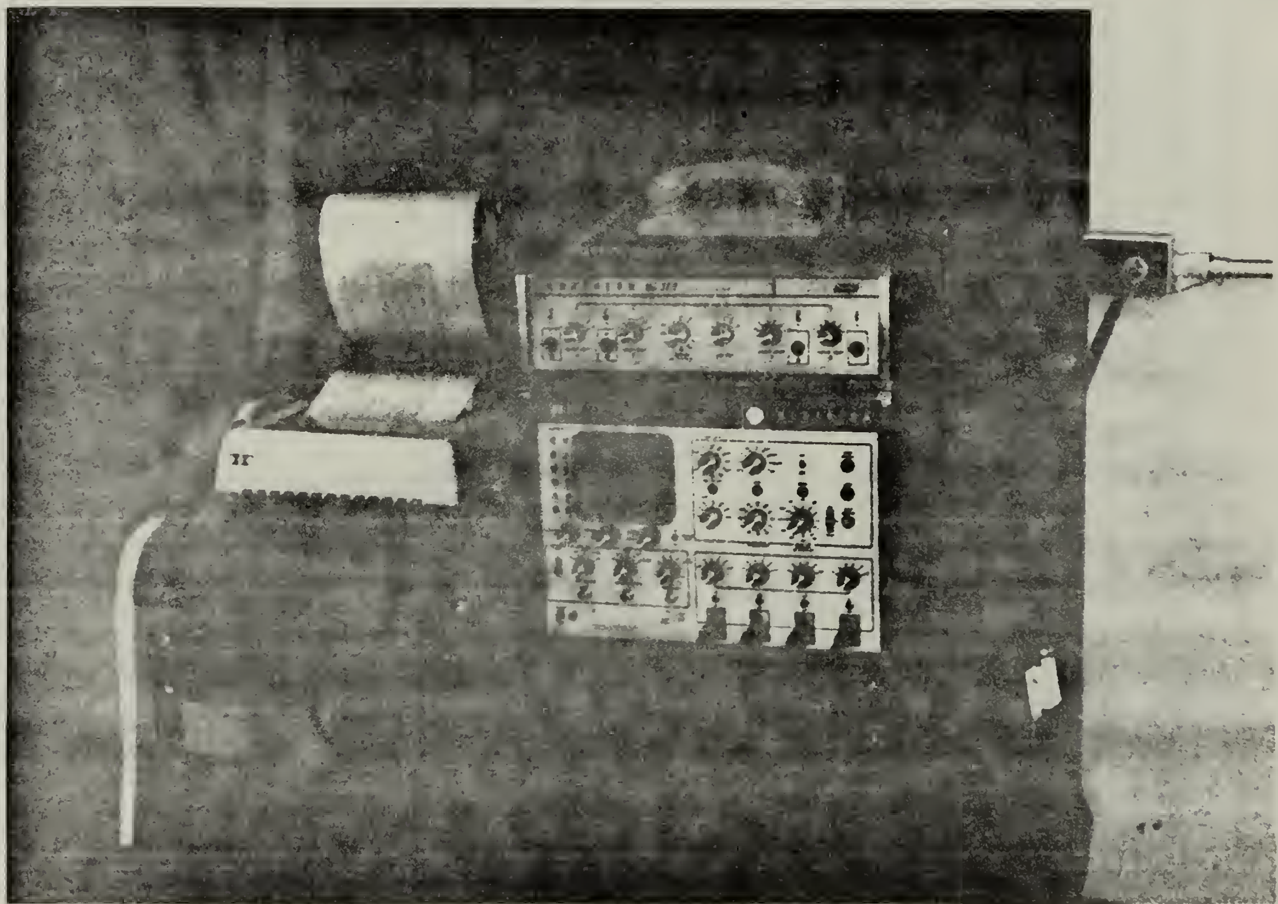


FIGURE D-3. DATA ANALYSIS EQUIPMENT

APPENDIX E.

TEST PROPELLER

The test propeller is a modified Michigan Wheel propeller model PJ-74. This was chosen so that readily accessible, inexpensive propellers could be obtained and easily modified to identify parameter variations. This particular (PJ-74,MOD 1) modification consisted of milling the blade leading edge profile so that it came out of the hub radially normal to the Lab. The low pressure face only was shaped to regain a foil crossection. Additionally the propeller tips were trimmed to obtain an exact (instead of nominal) 10 inch diameter (figure E-1). The Pitch/ Diameter ratio is .925.

Three steady force propeller tests were performed on this propeller operating in the generated wake at 1200 and 1800 RPM, and without the wake at 1500 RPM. As expected, all were coincident.

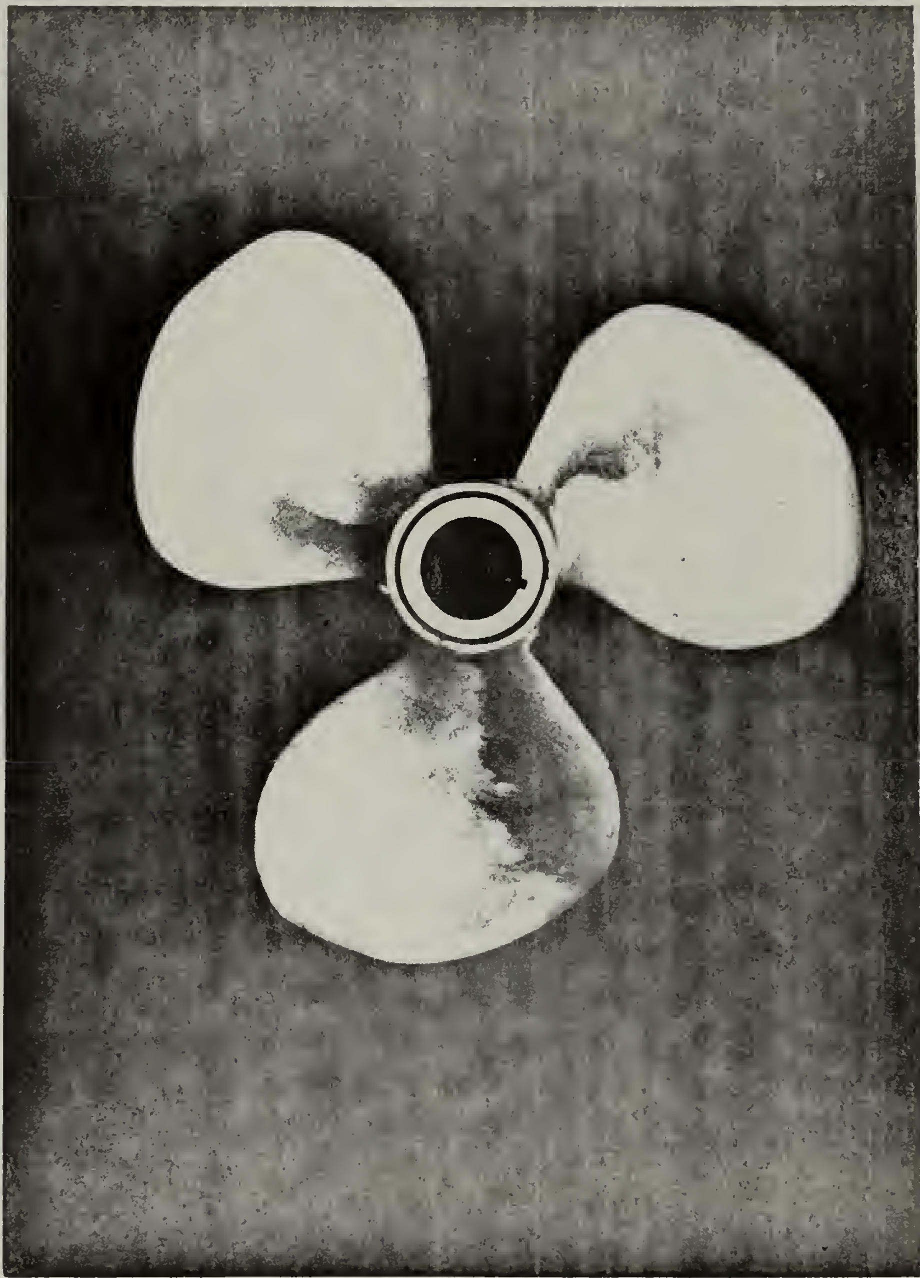


FIGURE E-1. TEST PROPELLER (PJ-74 MOD 1)

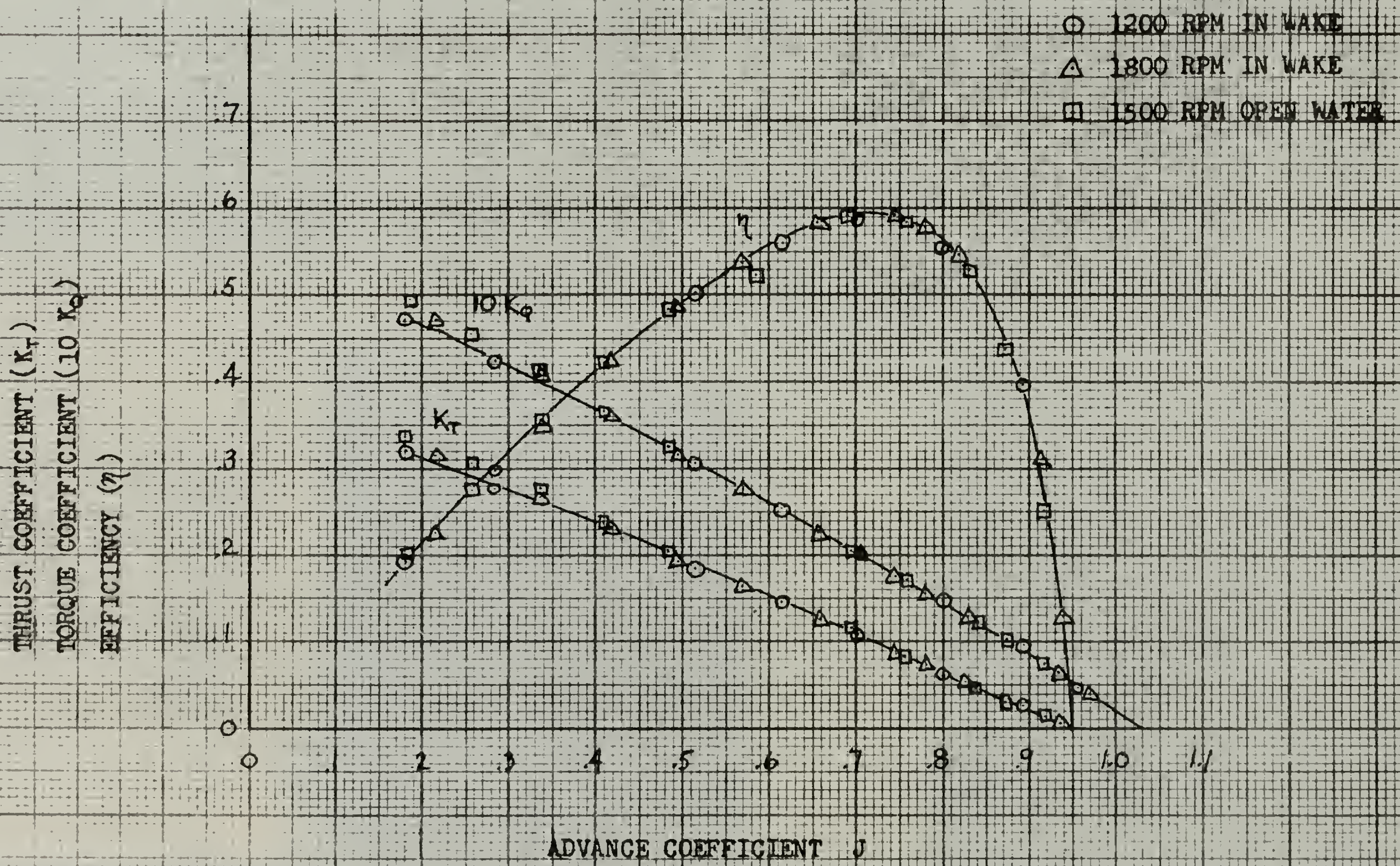


FIGURE E-2. PROPELLER AVERAGE CHARACTERISTICS (PJ-74 Mod. 1)

Thesis 127224
P46174 Pfister
Development of a procedure to measure unsteady propeller forces.